Phytoplankton Early Warning Approaches for Salmon Farmers in Southwestern New Brunswick: Aquaculture Collaborative Research and Development Program Final Project Report

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Aquaculture Collaborative Research and Development Program Final Project Report

by

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ABSTRACT

Chang, B.D., Martin, J.L., Page, F.H., Harrison, W.G., Burridge, L.E., LeGresley, M.M., Hanke, A.R., McCurdy, E.P., Losier, R.J., Horne, E.P.W., and Lyons, M.C. 2007. Phytoplankton early warning approaches for salmon farmers in southwestern New Brunswick: Aquaculture Collaborative Research and Development Program final project report. Can. Tech. Rep. Fish. Aquat. Sci. 2715: v + 108 p.

This project investigated the feasibility and cost-effectiveness of several potential early warning approaches for harmful algal blooms at salmon farms in southwestern New Brunswick (SWNB). The components of this 3-yr project included: training farm personnel on the sampling, identification, and counting of harmful algal species; implementation of high frequency phytoplankton monitoring by farm staff at selected salmon farms; retrospective statistical analyses of existing monitoring data; laboratory experiments to determine threshold concentrations of selected harmful algae which can cause problems for farmed salmon; use of a water circulation model to predict the movements of blooms which may affect salmon farms; evaluation of the effectiveness of a light sensor array for bloom detection; and evaluation of the usefulness of satellite imagery for bloom detection.

Training sessions for farm workers were held in July 2004 and May-June 2005. Training was provided on sampling techniques, the use of microscopes, and the identification and counting of harmful phytoplankton species. Phytoplankton monitoring was conducted by trained staff at four farms near Grand Manan Island in 2004 and at two farms near Grand Manan Island, one farm in Passamaquoddy Bay, and one farm on the SWNB mainland coast in 2005. The goal was to have farm workers collect and analyze samples approximately daily from late spring to early fall. On average, samples were collected in about 60% of days in 2004 (July-September) and 75% in 2005 (late May-September), while the numbers of samples analyzed represented <10% of the days in 2004 and <15% in 2005. Retrospective analyses of patterns of abundance were conducted on data collected by DFO since 1987 on 11 species of harmful algae. Laboratory experiments to determine lethality levels for salmon smolts were conducted on four algal species. A water circulation model was used to predict the spatial and temporal origins of algal blooms that could impact salmon farms in the Grand Manan Island area. A light sensor array was deployed in 2005 in Passamaquoddy Bay and it was able to measure changes in light irradiance during the day at depths 0-16 m; however, because there were no large blooms during the deployment, there was insufficient phytoplankton abundance data to allow adequate calibration of sensor data. Analyses of satellite images showed that it was possible to track general trends in chlorophyll levels in SWNB, but the methodology currently available could not provide an early warning of harmful algal blooms.

RÉSUMÉ

Chang, B.D., Martin, J.L., Page, F.H., Harrison, W.G., Burridge, L.E., LeGresley, M.M., Hanke, A.R., McCurdy, E.P., Losier, R.J., Horne, E.P.W., and Lyons, M.C. 2007. Phytoplankton early warning approaches for salmon farmers in southwestern New Brunswick: Aquaculture Collaborative Research and Development Program final project report. Can. Tech. Rep. Fish. Aquat. Sci. 2715: v + 108 p.

Ce projet de trois ans avait pour but d'établir la faisabilité et la rentabilité de plusieurs méthodes possibles de détection rapide de poussées d'algues nuisibles dans des sites de salmoniculture du Sud-Ouest du Nouveau-Brunswick (SONB). Il comprenait les éléments suivants : formation du personnel des salmonicultures dans les techniques d'échantillonnage, d'identification et de dénombrement d'espèces d'algues nuisibles; exécution par le personnel de certaines salmonicultures d'activités de surveillance fréquente du phytoplancton; analyses rétrospectives des données de surveillance existantes; expériences de laboratoire en vue d'établir les seuils de concentration de certaines algues nuisibles pour le saumon d'élevage; utilisation d'un modèle d'étude de la circulation de l'eau en vue de prévoir les mouvements des algues qui peuvent nuire aux salmonicultures; évaluation de l'efficacité d'un réseau de détecteurs optiques pour déceler les poussées; et évaluation de l'utilité de l'imagerie satellitaire pour déceler les poussées.

Les séances de formation des travailleurs salmonicoles ont eu lieu en juillet 2004 et en mai et juin 2005. La formation portait sur les techniques d'échantillonnage, l'utilisation de microscopes et l'identification et le dénombrement d'espèces de phytoplancton nuisibles. En 2004, le personnel dûment formé de quatre exploitations près de l'île Grand Manan a effectué une surveillance du phytoplancton, et en 2005, la surveillance s'est déroulée dans deux exploitations près de l'île Grand Manan, dans une exploitation de la baie Passamaquoddy et dans une ferme située sur la partie continentale du SONB. On avait demandé aux travailleurs aquacoles de prélever et d'analyser des échantillons presque tous les jours, entre la fin du printemps et le début d'automne. En moyenne, on a prélevé des échantillons environ six jours sur dix en 2004 (de juillet à septembre) et 7,5 jours sur dix en 2005 (de la fin mai à septembre), tandis qu'on en a analysé moins d'un jour sur dix en 2004 et moins d'un jour et demi sur dix en 2005. Afin de déterminer les répartitions de l'abondance, on a effectué des analyses rétrospectives des données prélevées par le MPO depuis 1987 sur onze espèces d'algues nuisibles. On a mené des expériences en laboratoire sur quatre espèces d'algues pour en déterminer les niveaux de létalité sur les smolts de saumon. Un modèle d'étude de la circulation de l'eau a été utilisé pour prévoir les origines spatiales et temporelles des proliférations d'algues qui pourraient avoir une incidence sur les exploitations salmonicoles autour de l'île Grand Manan. Un réseau de détecteurs optiques déployé en 2005 dans la baie Passamaquoddy a permis de mesurer les changements dans l'éclairement énergétique durant le jour à des profondeurs de 0 à 16 m. Cependant, en l'absence d'importantes proliférations d'algues durant le déploiement, il n'y avait pas assez de données sur l'abondance du phytoplancton pour permettre un étalonnage adéquat du capteur. Des analyses des images par satellite ont indiqué qu'il était possible de suivre la tendance générale du niveau de chlorophylle dans le SONB, mais que la méthode actuellement disponible ne pouvait pas permettre un avertissement rapide de la présence des proliférations d'algues nuisibles.

INTRODUCTION

Phytoplankton blooms naturally occur in the inshore and offshore areas of the lower Bay of Fundy (Martin et al. 2001a). They may originate in offshore areas (White and Lewis 1982; Martin and White 1988; Martin and Wildish 1994) and be transported by water into the inshore areas where the salmon farms are located, or they may originate within an inshore area (Martin et al. 2001a) When phytoplankton blooms occur in salmon farming areas, the health of the caged salmon may be compromised. This has happened several times within the past decade, especially in the Passamaquoddy Bay area (Martin et al. 2001a). Blooms occur less frequently in the Grand Manan area, but a bloom in 2003 caused severe economic losses at several farms along the eastern shore of Grand Manan Island (Martin et al. 2006a). Phytoplankton can cause physical damage to the gills of fish, introduce toxins into the fish, and/or deplete or elevate the levels of dissolved oxygen in the water (Bruslé 1995). The result may be mortality in smolts and loss of growth in all sizes of caged salmon. Introduction of fall S_0 smolts (age <1 yr) into cages may need to be delayed due to their sensitivity to phytoplankton blooms. These effects have caused millions of dollars of lost revenue to the affected salmon farmers, and insurance companies are interested in knowing what farmers are doing to mitigate potential phytoplankton-related losses.

As a result of the economic consequences, the salmon farmers would like to have a monitoring approach that warns them of an upcoming, potentially harmful phytoplankton event, a toolbox of mitigation actions, and a table of phytoplankton species and cell concentrations that are likely to cause production losses. Warnings of hours to days are useful since farmers could act on the information by adjusting harvesting schedules, delaying the entry of smolts, and adjusting feeding schedules and medication treatments. The purpose of this project was to investigate the feasibility and cost-effectiveness of several potential early warning approaches, and to estimate concentration thresholds for production losses in several of the dominant harmful algal species.

It is well known that phytoplankton blooms are notoriously difficult to predict. Scientists in various parts of the world have been working on this for decades with little success to date. Two decades of monitoring phytoplankton within the southwestern New Brunswick (SWNB) area of the Bay of Fundy have indicated that the general seasonal timing of the blooms of some species is quite consistent, and hence predictable, to some extent (Wildish et al. 1988, 1990; Martin et al. 1995, 1999, 2001b, 2006b). The inter-annual deviations in the magnitude of the blooms and slight variations in the timing of the blooms, and hence the onset and magnitude of a bloom in a given year, are not readily predictable from data collected at biweekly or weekly intervals. However, some initial statistical analyses have indicated that sophisticated time series analysis techniques have potential for statistical forecasting of phytoplankton abundance.

Our understanding of phytoplankton dynamics and patterns in the SWNB portion of the Bay of Fundy led us to believe that:

- higher frequency sampling programs were needed at critical locations and times;
- statistical analysis approaches needed to be applied to time series of individual phytoplankton species to determine the potential for forecasting bloom events;
- the usefulness of satellite imagery and other technologies for detecting offshore phytoplankton blooms in the Bay of Fundy needed to be investigated; and

- we needed information on the critical threshold levels of harmful algae which cause harm to farmed salmon.

These conclusions are consistent with the international state-of-understanding as it pertains to phytoplankton blooms and as it has been articulated in the international GEOHAB (Global Ecology and Oceanography of Harmful Algal Blooms) program (Martin 2002). We recognized that it would take many years to fully develop an effective phytoplankton early warning system for the SWNB area; hence, the objective of this study was not to fully develop such a system. The objectives were aimed at establishing the feasibility and usefulness of some existing technologies, and for establishing the need for high frequency sampling. Refinements of the approach can be made at a latter date if the approaches prove to be effective.

This joint industry-government project, funded by the Fisheries and Oceans Canada (DFO) Aquaculture Collaborative Research and Development Program (ACRDP), provided a unique opportunity to pursue such research. The ACRDP funding was essential for providing the salaries of the qualified people needed to conduct this work, since the industry did not have the expertise or resources, and DFO science did not have the staff time or regular resources to mount the necessary effort.

The research program was aimed at addressing some of the immediate needs of the salmon farmers in the SWNB area, contributing information necessary for the design of a cost-effective operational phytoplankton monitoring and warning approach, and contributing fundamental information to the development of an understanding of phytoplankton dynamics in SWNB. The work provided a first attempt at determining whether several available sampling approaches were feasible and effective in giving an early warning of potentially harmful phytoplankton events. It was not the aim of the proposed project to predict the formation of phytoplankton blooms from mechanistic considerations. Rather, the aims were to implement several strategies for sampling and data analysis that would provide information concerning:

1) the temporal and spatial scales of variability in the concentration of potentially harmful phytoplankton species;
2) the effectiveness of sampling and data analysis strategies for detecting the presence of potentially harmful phytoplankton species;
3) the effectiveness of the approaches used for sampling and data analysis for detecting and projecting a temporal trend in the abundance of a harmful algal species;
4) the algal cell concentrations that trigger changes in the behavior and health of contained salmon; and
5) the ability of a tidal circulation model to estimate the susceptibility of a farm to a nearby plankton bloom.

This information could then be used as a foundation for the consideration of designs for a cost-effective phytoplankton monitoring and early warning system that could potentially be implemented and maintained by the industry with the appropriate involvement of others. The work would also provide a basis for developing further collaborative work with ocean industries, research institutions and research programs, and for testing new equipment such as *in situ* electronic sampling methodologies that appear to have potential for helping to address the phytoplankton issues.

PROJECT COMPONENTS

The project was comprised of the following components:

1. Training and communication of information on harmful algal blooms between DFO Science and the SWNB salmon aquaculture industry.
2. Enhanced phytoplankton monitoring at fish farms.
3. Retrospective analyses of abundance patterns in harmful algal species.
4. Determine the threshold concentrations of some phytoplankton species which are harmful to farmed salmon.
5. Use of a water circulation model to predict the movements of phytoplankton blooms affecting fish farms.
6. Test the usefulness of a real-time moored light sensor to detect phytoplankton blooms.
7. Evaluate the usefulness of satellite imagery as a tool for detecting offshore phytoplankton blooms in the Bay of Fundy.

Summaries of the results of each component are presented below. Additional results can be found in the Appendices and in separate published reports (see Appendix 1).

1: Training and communication of information on harmful algal blooms between DFO Science and the SWNB salmon aquaculture industry (J.L. Martin, M.M. LeGresley)

Much of the success of the project and the empowerment of industry with the ability to maintain an ongoing routine phytoplankton monitoring program depended upon this aspect of the project. Members of the industry must be able to reliably conduct much of the phytoplankton sampling, and must learn to accurately identify and assess the abundance of the phytoplankton species that are potentially harmful to the caged fish.

Project planning meetings were held on 16 March and 28 May 2004 at the St. Andrews Biological Station (SABS). These meetings dealt with project objectives, the project budget, the responsibilities of the various partners, purchasing of equipment, and selection of priority field sampling sites. Meetings were held on 1 September and 10 December 2004 to provide industry partners with updates on activities and results. A planning meeting for the second field season was held on 11 May 2005. A final project meeting was held on 8 November 2006 to present a summary of the project's results to the industry partners. Reports on some aspects of the project were also given at various scientific conferences (see Appendix 1).

Twelve farm workers were trained in microscope use, phytoplankton sampling techniques, phytoplankton identification, and record keeping on 7 July 2004, at SABS, just prior to commencement of the first season of enhanced monitoring. Fourteen farm workers (including three who had been trained in 2004) received training just prior to the start of the 2005 field season, on 26-27 May and 2 June 2005, at SABS. A list of training session participants and information provided to participants is included in Appendix 2.

A telephone/voice-mail and e-mail system was set up to allow rapid communication between DFO scientists and industry participants in the enhanced monitoring component. This allowed industry participants to report sampling information to DFO Science, and also allowed DFO Science to communicate the latest results to the industry participants. Communications were maintained on a regular basis throughout the field sampling seasons for enhanced monitoring in 2004 and 2005.

2: *Enhanced phytoplankton monitoring at fish farms* (*J.L. Martin, M.M. LeGresley, B.D. Chang, S. Tielesh*)

The main aspect of this component was the collection by farm workers of approximately daily samples of phytoplankton (surface samples and vertical tows) and environmental parameters, as well as the identification and counting of selected algal species, using the methods described in Appendix 2. In addition, it was proposed that DFO scientists would conduct occasional 12- to 13-h periods of intensive sampling at selected farms. The high frequency sampling was to be used to test the hypothesis that the onset of a phytoplankton bloom in an area could be detected and forecast by daily phytoplankton monitoring at the farms.

The species chosen for identification and enumeration from water samples included species known to cause problems in SWNB salmon farms, or species known to cause problems in salmon farms in other geographical areas and also known to exist in SWNB. The following species were chosen: *Alexandrium fundyense*, *Chaetoceros convolutus*, *C. socialis*, *Corethron criophilum*, *Ditylum brightwellii*, *Eucampia zodiacus*, *Leptocylindrus minimus*, *Mesodinium rubrum*, and *Pseudo-nitzschia* spp. Another species, *Membraneis challengeri*, which had not previously been observed in SWNB, was included after it was observed in relatively high numbers in 2005.

It was proposed that surface water samples and vertical tows would be taken daily during May through October at four to six locations in 2004 and 2005: two to three in Passamaquoddy Bay and two to three in the Grand Manan area. These areas were initially proposed because these were the salmon farming areas that had recently experienced harmful phytoplankton blooms. The number of locations would depend on the number of participating companies. The samples would be collected by the participating farmers. One set of samples would be preserved for later examination by DFO phytoplankton experts (J.L. Martin and M.M. LeGresley). The other set of samples would be examined on site by trained farm workers using standardized equipment and examination protocols (field microscope, standardized sample preparation, etc.). The identified species and counts would be recorded by the farm workers and reported to the DFO researchers.

In 2004, we had four participating companies, with one farm per company conducting enhanced monitoring. Unfortunately, we were unable to have any sites in Passamaquoddy Bay, because no farms were operating in this area due to an outbreak of infectious salmon anemia (ISA), so all four sites in 2004 were in the Grand Manan Island area. In 2005, we also had four sites, with two in the Grand Manan Island area (including one of the sites used in 2004), one in Passamaquoddy Bay, and one on the mainland shore of SWNB.

In 2004, the four farms collected on average slightly more than 60% of the potential number of samples per farm between July and September (100% would mean samples were collected every day between the first and last days of sampling at the site). In 2005, the four farms collected on average 75-76% of the potential number of samples per farm between late May and September, a significant improvement over 2004.

Reports on sample counts done by farm workers were received much less frequently. In 2004, the numbers of daily count forms submitted averaged 3-6% of the potential number (100% would mean counts were submitted for every day between the first and last days of sampling at the site). In 2005, the numbers of daily count forms submitted averaged 11-13% of the potential, slightly higher than the previous year. Some of the reasons for these low numbers included: workers were busy with other tasks with higher priorities; phytoplankton identification and counting were more tedious and required much more time than sample collection; there were no large blooms at any of the enhanced monitoring sites during the project; and in some cases, the microscopes were moved to other farms which were experiencing phytoplankton problems.

A. fundyense and *P. delicatissima* were the most abundant species in both years; both showed higher levels in 2004 than in 2005. The only other species which reached historical maximum bloom levels was *M. rubrum* at one site in 2005. *M. challengeri* was observed for the first time in SWNB in 2004, when only low numbers were observed, and showed high abundance (up to 55 000 organisms·L^{-1}) in 2005.

Counts reported by farm workers generally showed similar trends in abundance as counts by DFO of the same samples or of samples taken at approximately the same time. However, some discrepancies did occur: when a species occurred at high abundance levels, farm counts were often higher than DFO counts, while when low abundance levels were reported by DFO analyses, farm workers often did not record any presence of the species.

One 12-h intensive sampling event was conducted (plankton sampling every 3-4 h from 08:00 to 19:00 Atlantic Daylight Time) at farm 002 (Long Island, eastern Grand Manan) on 23 September 2004. Phytoplankton abundance was low in all samples collected, and it was decided not to conduct additional 12-h sampling events.

The low frequency of phytoplankton counts by industry participants, together with the low abundance of most species during this study, meant that there was insufficient data which could be statistically analyzed to determine if there is predictive power in the enhanced monitoring data. Nevertheless, the industry partners felt that this component of the project was very worthwhile, especially the training of staff in the sampling, identification, and counting of harmful phytoplankton species. The phytoplankton counts that were done by farms allowed them to confirm if harmful blooms were occurring where there were suspicions of phytoplankton problems (e.g. due to discoloration of water or abnormal fish behavior). It also provided an indication of when farms should increase the frequency of monitoring, such as when phytoplankton levels were approaching the threshold levels for mortality or sublethal effects on farmed fish. This also provided farms timely data to help in deciding when to implement management decisions such as to stop feeding. See Appendix 3 and Martin et al. (2006c) for additional results from the enhanced monitoring component.

3: Retrospective analyses of abundance patterns in harmful algal species *(J.L. Martin, C.D. Hastey, A.R. Hanke, F.H. Page)*

The purpose of this aspect was to analyse and summarise existing phytoplankton monitoring data from the perspective of characterising the spatial and temporal characteristics of the cell concentrations of dominant harmful algae species. The phytoplankton community in SWNB has been monitored at several locations and at weekly to monthly intervals since 1987 (Wildish et al. 1988, 1990; Martin et al. 1995, 1999, 2001b, 2006b). The data have been archived in an electronic database and were used to estimate statistics concerning bloom characteristics such as the time of onset, duration of bloom, maximum concentration, number of blooms per year, spatial extent of blooms and inter-annual time trends in the bloom characteristics. The data also show which species are likely to bloom every year and which species only occasionally. This information is useful to farmers for their mitigation considerations, in that once a bloom begins, they will have some estimate of how long the bloom is likely to persist, how large the cell concentrations are likely to get, and over what spatial scale the bloom is likely to occur.

Retrospective analyses were completed on *Alexandrium fundyense, Chaetoceros convolutus, C. socialis, Corethron criophilum, Ditylum brightwellii, Eucampia zodiacus, Leptocylindrus minimus, Mesodinium rubrum,* the *Pseudo-nitzschia delicatissima* group, the *P. seriata* group, and *Pseudo-nitzschia* sp. Results for *A. fundyense* have been reported in Page et al. (2005, 2006). Some general trends for this species are:

- *A. fundyense* blooms occur every year:
    - one or more bloom events occur each year.
    - peak cell counts are ≥ 100 000.
- seasonal variation:
    - blooms occur between day ~130 (May) and day ~300 (October).
    - more than one bloom event usually occurs per year.
    - the timing and duration of events are variable.
- annual maximum in cell concentration:
    - usually does not occur in the first bloom event.
    - usually occurs in the latter half of an event.

A summary of the findings for all species examined in this component is found in Appendix 4. Additional details are being published in a series of technical reports (Martin et al. 2007a, b; other reports in preparation).

4: Determine the threshold concentrations of some phytoplankton species which are harmful to farmed salmon *(L.E. Burridge, M.C. Lyons, M.M. LeGresley, E.P. McCurdy, C. Davidge, J.L. Martin, K.G. MacKeigan, C. Reid)*

The purpose of this component was to estimate the concentrations (cell or chain counts) at which harmful algal blooms may cause loss of production and ultimately harm to farmed salmon (threshold levels). This work was intended to help determine trigger points for farmers to initiate husbandry strategies on their farms to mitigate the impacts of the phytoplankton on the caged fish.

Species of potentially harmful algae commonly found in the SWNB area were cultured in the laboratory and salmon smolts (~450 g; supplied by participating fish farms) were exposed to different concentrations of algal monocultures to determine the concentration thresholds that would cause changes in feeding behavior and damage to fish gills, as well as lethality. Four species (*Alexandrium fundyense*, *Chaetoceros socialis*, *Ditylum brightwellii*, and *Pseudo-nitzschia delicatissima*) were selected, because they had been suggested as having caused problems to salmon at cage sites in SWNB in recent years. Although *Mesodinium rubrum* has been implicated to have caused problems for farmed salmon in SWNB, it was not included in the list due to the fact that it is very difficult to culture this species.

The salmon smolts were tested by 24-h exposure to different concentrations of algae. The fish were tested in static seawater in 150-L aquaria, with five smolts per aquarium. A range of concentrations, plus a control, were tested for each of the algae species. Three replicates were done for each algal species, resulting in sample sizes of 15 fish for each algal concentration and the controls. A table summarizing the results is presented below.

Algal species	**Estimated lethality (24-h exposure)**
Alexandrium fundyense	LC50 = 614 000 cells·L^{-1}.* No observed effect concentration (NOEC) = 250 000 cells·L^{-1}.
Ditylum brightwellii	No mortalities or behavioural responses at up to 1 million cells·L^{-1}.
Chaetoceros socialis	No mortalities or behavioral responses at 400 000 chains·L^{-1}. One mortality and some behavioral responses at 4 million chains·L^{-1}.
Pseudo-nitzschia delicatissima (2 clones)	No mortalities or behavioral responses at up to 128 million cells·L^{-1}. No domoic acid was detected in concentrated pellets from these clones.

* The concentration of cells that produced mortality is specific to our culture and exposure conditions.

A. fundyense was the only alga that killed salmon. Production of PSP (paralytic shellfish poisoning) toxins is variable among cultures (or blooms) and between growth stages. For this reason, the predictive value of cell counts is limited. We measured the PSP equivalents (eq) in the cell cultures used in this study. The 614 000 cells·L^{-1} threshold is only valid for a culture (or bloom) producing ~33 pg PSP eq·cell^{-1}. Cultures generally produce less toxins than blooms in the field (J.L. Martin, pers. comm.). This reality has implications for risk assessment. Our exposure regimen of 24-h static exposure may be an overestimate of the actual exposure period experienced by fish at cage sites, but the level of PSP is lower than has been reported in cells collected in the field (60-70 pg PSP eq·cell^{-1}).

The LC50 estimate (cells·L^{-1}) for *A. fundyense* presented here is a concentration that has been observed in SWNB where the duration of exposure may be shorter than 24 h, but the concentration of PSP may be higher. Anecdotal information from fish farmers suggests that *A. fundyense* concentrations up to 300 000 cells·L^{-1} did not affect salmon in cages (E. Gagné, Cooke Aquaculture Inc., St. George, NB, pers. comm.).

For the other species, no mortalities or behavioral effects were observed at concentrations much higher than have been observed in SWNB. A report with the complete results for this component is being prepared for publication in a scientific journal.

5: *Use of a water circulation model to predict the movements of phytoplankton blooms affecting fish farms* (*B.D. Chang, R.J. Losier, F.H. Page, D.A. Greenberg, J.D. Chaffey*)

The spatial and temporal origins of water that flows through a farm were estimated on tidal time scales using an existing numerical model of the mean tidal circulation in the SWNB area. This information can be used to estimate the likelihood of a bloom being transported to or from a farm within one or more tidal cycles.

We conducted this work for fish farms in the Grand Manan Island area. Previously calculated estimates of the tidal excursion areas around fish farms were used to predict the likelihood that a bloom occurring at a farm could be transported to neighboring farms during one tidal cycle (12.4 h). New work examined the movement of water originating from points in a grid surrounding Grand Manan Island, tracking the water movement over a longer period (eight tidal cycles or about 4 d). Such time frames were considered useful for contingency planning at farms. For example, if a bloom was observed at a location which, according to the model, would likely be transported to the farm in 4 d, the farm could start preparations for management action (such as cessation of feeding or early harvesting), while at some shorter time interval, management actions would actually be implemented.

A short report on this component is presented in Appendix 5. Complete results are published in a separate technical report (Chang et al. 2007).

6: *Test the usefulness of a real-time moored light sensor to detect phytoplankton blooms* (*E.P.W. Horne, R.J. Losier, B.D. Chang, E.P. McCurdy, F.H. Page*)

This component proposed to moor a passive light sensor array at one or more farms in SWNB. The sensor array recorded the intensity of the 490-nm wavelength light at different depths in the upper water column. The 490-nm wavelength was used since it is in the middle of the phytoplankton chlorophyll absorption range. Data was collected from approximately 05:00-20:00 Atlantic Daylight Time daily. Data was missing from some days or partial days due to equipment maintenance. The data would give an indication of the temporal variability in gross phytoplankton on time scales that are not feasible to monitor using water bottle sampling approaches. The equipment was deployed near enhanced phytoplankton monitoring stations so the intensity signal could be compared to the phytoplankton species count data acquired as part of the activities described above.

This type of equipment is being used as part of a larger state-of-the-art research program headed by Dalhousie University in their coastal monitoring and forecasting program. The application of the technology to the SWNB area will enable us to take advantage of their technical knowledge, and provides a cost-effective approach for evaluating the potential of this technology for detecting and forecasting phytoplankton blooms. The advantage of using such equipment, if it proves to be useful, is that the data can be continuously uploaded to a land base and processed for display on the web, triggering of an alarm to designated growers, or, among other things, e-mailing to interested parties. The moored array may also be directly useful to offshore farms if development in the offshore is pursued and a spatial array of sensors is desired for warning of plankton blooms. To limit the cost of this evaluation, we used existing equipment belonging to Ed Horne (DFO, Bedford Institute of Oceanography). Some upgrading of this equipment was required.

An initial attempt to deploy the light sensor array at a farm at Grand Manan Island in the fall of 2004 was not successful due to delays in obtaining and deploying some equipment components. The equipment was deployed at a farm in Passamaquoddy Bay in June-August 2005. The sensor array did detect changes in light irradiance during the day and decreases in light intensity with depth. Unfortunately, there were no large phytoplankton blooms at this site during the deployment, so we did not have enough data to allow us to correlate the light irradiance values with phytoplankton abundance data. More details on this project component are presented in Appendix 6.

*7: **Evaluate the usefulness of satellite imagery as a tool for detecting offshore phytoplankton blooms in the Bay of Fundy*** *(W.G. Harrison, J.L. Martin, H. Maass)*

Historical Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite images (1997-2004) were examined for evidence of being able to detect and track phytoplankton blooms within the lower Bay of Fundy. We examined the images for evidence of large-scale and intense blooms of *Alexandrium fundyense*. Time series of satellite-based indicators of phytoplankton were generated for specific locations and compared with existing phytoplankton count data collected from the Prince 5 and the Wolves Islands monitoring stations.

The SeaWiFS satellite images are routinely gathered and processed by the Biological Oceanography Section of the DFO Ocean Science Division (Bedford Institute of Oceanography, Dartmouth, NS) as part of the DFO Atlantic Zonal Monitoring Program (AZMP) and other efforts. The images can be used qualitatively as color images, or processed to give a quantitative estimate of the total amount of chlorophyll in the near surface water. Biweekly composite images are routinely produced and posted on a web site. The individual images are stored for additional analyses. This work required reprocessing of archived satellite images and extraction of intensity data from the lower Bay of Fundy area. The work required relatively few resources and provided an opportunity to begin to examine the potential for some existing satellite-based remote sensing outputs as a tool for the aquaculture industry in the Bay of Fundy.

The purpose of this component was to help address the situation in which blooms originate offshore of the fish farming areas in Grand Manan and SWNB. Ideally, the images would indicate the movement of a bloom toward the inshore areas and the tidal models would estimate the transport pathways of the bloom into the fish farms once the bloom reached the inshore area. The satellite imagery may also be directly useful to offshore farms if development in the offshore is pursued.

The usefulness of satellite images for detecting phytoplankton blooms in the Bay of Fundy is sometimes compromised by the high turbidity of the Bay of Fundy water. Furthermore, the images do not indicate the type of species that may be causing changes in water color. It was hoped that images would give a qualitative indication of the presence of a bloom, and the species identification limitations could be overcome to some extent by examining the phytoplankton samples collected at weekly to biweekly intervals at the existing offshore phytoplankton and hydrographic monitoring stations (the Wolves Islands and Prince 5). However, our analyses seem to indicate that, while the satellite chlorophyll data do appear to track bulk chlorophyll, they do not appear to adequately track *Alexandrium* blooms. A short report on this project component is found in Appendix 7. Complete results are published in a separate technical report (Harrison et al. 2007)

Despite the limitations, the use of satellite imagery is gaining popularity world wide and its capability is continuously being improved and explored in other parts of the world. The imagery is often free and readily available on web sites and hence presents the potential for a very cost effective early warning indicator of plankton blooms. Future developments in analytical techniques may improve the ability of satellite imagery to detect blooms.

SUMMARY

The participating farms felt that the project was useful, especially the enhanced monitoring component, which provided training of farm staff in the collection of samples, microscope use, and phytoplankton identification and counting. The frequency of sample collection by farm staff was relatively good, and improved in the second year. Unfortunately, the low frequency of phytoplankton counts by farm staff, together with the low abundance of most species, meant that there was insufficient data to allow statistical analyses to test the predictive capability (as an early warning of blooms) of high frequency sampling; however, the frequency of phytoplankton counts at some farms could provide a warning when phytoplankton levels were approaching levels when harmful effects could occur, thus triggering increased frequency of phytoplankton monitoring, as well as alerting the farm of the need for possible farm management actions (such as cessation of feeding). The retrospective data analyses provided information on general trends for blooms of several species. The threshold component provided information on phytoplankton levels that may be harmful to farmed fish. The water circulation model provided predictions of how blooms may move toward or from farms. The light sensor array and satellite imagery showed some promise for detecting blooms, but both require additional development.

ACKNOWLEDGEMENTS

Funding for this project was provided by the Fisheries and Oceans Canada (DFO) Aquaculture Collaborative Research and Development Program (ACRDP), DFO Science, Cooke Aquaculture Inc., Aqua Fish Farms Ltd., Heritage Salmon Ltd., Stolt Sea Farm Inc., and Admiral Fish Farms Ltd. The New Brunswick Salmon Growers' Association (NBSGA) assisted with project coordination and administration. We thank the following individuals who assisted in the project: E. Gagné (Cooke Aquaculture); P. Fitzgerald and V. Pedersen (Heritage Salmon); C. Davidge (Stolt Sea Farm); C. Saulnier and S. McGrattan (Aqua Fish Farms); E. Kearney (Admiral Fish Farms); other participating farm staff; J. Smith and S. Smith (NBSGA); and S. Tielesh (DFO summer student, 2005). D. Greenberg and J. Chaffey (DFO Bedford Institute of Oceanography) provided assistance with the water circulation model.

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Appendix 1
Lists of presentations and publications

PRESENTATIONS (name of presenter is underlined)

Aquaculture Canada 2004, Quebec City, 17-20 October 2004.

- Chang, B.D., Page, F.H., Martin, J.L., Harrison, W.G., Horne, E.P.W., Burridge, L.E., LeGresley, M.M., Hanke, A.R., McCurdy, E.P., and Smith, J.A. Phytoplankton early warning approaches for salmon farmers in southwestern New Brunswick.
- Page, F.H., Hanke, A.R., Martin, J.L., LeGresley, M.M., Chang, B.D., and McCurdy, E.P. Characteristics of *Alexandrium fundyense* blooms that affect caged salmon in the Bay of Fundy.

11th International Conference on Harmful Algae, Cape Town, South Africa, 14-19 November 2004.

- Martin, J.L., Page, F.H., LeGresley, M.M., Haya, K., and Chang, B.D. Salmon mortalities associated with a bloom of *Alexandrium fundyense* in 2003 and subsequent early warning approaches for industry.
- Page, F.H., Martin, J.L., Hanke, A.R., and LeGresley, M.M. Temporal and spatial variability in the characteristics of *Alexandrium fundyense* blooms in the coastal zone of the Bay of Fundy. (Poster)

ICES Oceanography Committee, Working Group on Harmful Algal Bloom Dynamics, Flødevigen, Norway, 4-7 April 2005

- Martin, J.L. Trends in *Alexandrium fundyense* cell densities in the Bay of Fundy, eastern Canada.

Aquatic Toxicity Workshop, 2-5 October 2005, Waterloo, ON.

- Burridge, L.E., Martin, J.L., Lyons, M.C., LeGresley, M.M., and Chang, B.D. Lethality of microalgae to farmed Atlantic salmon. (Poster)

ICES Oceanography Committee, Working Group on Harmful Algal Bloom Dynamics, Gdynia, Poland, 3-6 April 2006

- Martin, J.L. *Alexandrium* measurements using remote sensing in Grand Manan Island in Bay of Fundy.
- Martin, J.L. *Alexandrium* cell abundance in Bay of Fundy.

12th International Conference on Harmful Algae in Copenhagen, 4-8 September 2006.

- Martin, J.L., Page, F.H., and LeGresley, M.M. *Alexandrium fundyense* – red tides, PSP shellfish toxicity, salmon mortalities and human illnesses in 2003-04 – before and after.
- Burridge, L.E., Martin, J.L., Lyons, M.C., LeGresley, M.M., and Chang, B.D. Lethality of microalgae to farmed Atlantic salmon. (Poster)

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Lists of presentations and publications

Aquaculture Canada 2006, Halifax, NS, 19-22 November 2006.

- Chang, B.D., Martin, J.L., Page, F.H., Harrison, W.G., Horne, E.P.W., Burridge, L.E., LeGresley, M.M., Hanke, A.R., Losier, R.J., and McCurdy, E.P. Phytoplankton early warning approaches for salmon farms in southwestern New Brunswick: project summary.
- Martin, J.L., LeGresley, M.M., Chang, B.D., and Page, F.H. Industry enumeration, early warning and hind-casting of harmful phytoplankton blooms in southwest New Brunswick.
- Burridge, L.E., Martin, J.L., Lyons, M.C., LeGresley, M.M., and Chang, B.D. Lethality of microalgae to farmed Atlantic salmon.

15th Annual Northeast Farmed Fish Health Management Workshop, Calais, ME, USA, 27 March 2007.

- Martin, J.L. and Burridge, L.E. Phytoplankton blooms and their lethality to Atlantic salmon in southwest New Brunswick.

ICES Oceanography Committee, Working Group on Harmful Algal Bloom Dynamics, Riga, Latvia, 10-13 April 2007.

- Martin, J.L., Burridge, L.E., and LeGresley, M.M. *Eucampia zodiacus* population trends in the Bay of Fundy.

10th Canadian Workshop on Harmful Algae, Mont-Joli, QC, 9-11 May 2007.

- Martin, J.L., Chang, B.D., and Page, F.H. Early warning and hind-casting of harmful algal blooms in southwest New Brunswick during 2004-05.
- Martin, J.L., Hastey, C.D., LeGresley, M.M., and Page, F.H. Temporal and spatial characteristics of phytoplankton that could potentially cause harm to farmed salmon in the Western Isles region of the Bay of Fundy.

Appendix 1
Lists of presentations and publications

PUBLICATIONS

Conference and Workshop Proceedings

Chang, B.D., Page, F.H., Martin, J.L., Harrison, G., Horne, E., Burridge, L.E., LeGresley, M.M., Hanke, A.R., McCurdy, P., and Smith, J.A. 2005. Phytoplankton early warning approaches for salmon farmers in southwestern New Brunswick. Aquacul. Assoc. Can. Spec. Publ. 9: 20-23.

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Technical reports

Chang, B.D., Losier, R.J., Greenberg, D.A., and Page, F.H. 2007. Use of a water circulation model to predict the geographic origins of phytoplankton blooms affecting salmon farms in the Grand Manan Island area, southwestern New Brunswick, Canada. Can. Tech. Rep. Fish. Aquat. Sci. 2703: iii + 64 p.

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Martin, J.L., Hastey, C.D., LeGresley, M.M., and Page, F.H. 2007. Temporal and spatial characteristics of the ciliate *Mesodinium rubrum* in the Western Isles region of the Bay of Fundy. Can. Tech. Rep. Fish. Aquat. Sci. 2714: iii + 27 p.

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Appendix 2
Training component

TRAINING SESSIONS

24 June 2004	
Industry participants	
Nathan Bass	Aqua Fish Farms
Todd Clinch	Stolt Sea Farm
Chris Davidge	Stolt Sea Farm
Evie Gagné	Cooke Aquaculture
Pepper Green	Cooke Aquaculture
Ryan Green	Cooke Aquaculture
Scott Guptill	Aqua Fish Farms
Caulder Huckins	Cooke Aquaculture
Lloyd Kirby	Cooke Aquaculture
Rupert Lambert	Heritage Salmon
Victoria Pedersen	Heritage Salmon
Karl Whelan	Stolt Sea Farm
Other participants	
Blythe Chang	DFO
Alex Hanke	DFO
Paul McCurdy	DFO
Fred Page	DFO
Instructors	
Murielle LeGresley	DFO
Jennifer Martin	DFO
Bill Shaw	Nikon Canada

26-27 May & 2 June 2005	
Industry participants	
Scott Bell	Stolt Sea Farm
Todd Clinch	Stolt Sea Farm
Tara Cooke	Cooke Aquaculture
Chris Davidge	Stolt Sea Farm
Andy Farquharson	Aqua Fish Farms
Cleo Fudge	Admiral Fish Farms
Evie Gagné	Cooke Aquaculture
Paul Herritt	Cooke Aquaculture
Luke Ingersoll	Cooke Aquaculture
Mitchell Ingersoll	Cooke Aquaculture
Mike Johnson	Cooke Aquaculture
Evan Kearney	Admiral Fish Farms
Stan McGrattan	Aqua Fish Farms
Eric Saulnier	Aqua Fish Farms
Other participants	
Les Burridge	DFO
Blythe Chang	DFO
Alex Hanke	DFO
Paul McCurdy	DFO
Fred Page	DFO
Simone Tielesh	DFO
Instructors	
Murielle LeGresley	DFO
Jennifer Martin	DFO

Training component

Phytoplankton sampling kit includes:

1 – phytoplankton net (20 µm mesh Nitex; 62 cm length; 23 cm diameter at mouth; 7 cm diameter at cod-end; 250 mL Mason jar attached at cod-end)

1 – pail (volume marked)
2 – 250 mL Mason jars
2 – plastic covers for Mason jars
1 – bag for plankton net
1 – roll of masking tape
1 – waterproof marker

1 – microscope with carrying case

2 – Sedgewick-Rafter slides
1 – thick cover slip
20 – thin cover slips
2 – regular microscope slides
50 – disposable pipettes
2 – pkg. lint-free Kimwipes
1 – slide storage box
100 – small 60 mL round bottles
50 – 250 mL clear bottles

1 – laminated species ID sheet
instructions – plankton tow & water sample

Photocopied data sheets
1 – binder
2 – pencils

Preservative for phytoplankton sampling:

FAA = formaldehyde : glacial acetic acid
(5 mL of FAA = 2.5 mL of formaldehyde and 2.5 mL of acetic acid)

Safe Handling / Personal Protection Procedures:

Please be careful - do not pour out the preservative from the sampling bottles.
Prevent contact with skin, eyes and clothing. Do not ingest.

This preservative contains formaldehyde which is known to be a carcinogen. Use appropriate handling procedures: If you come in contact with the preservative, flush the skin/eyes with clean water. Consult a physician if required.

Harmful Phytoplankton Field Sampling Procedure

Daily

- Record all sample information on data sheet provided.
- Collect whole water sample and vertical net haul. These will be picked up weekly by DFO.
- Count phytoplankton from net sample with Sedgewick-Rafter slide.
- Phone in results to DFO algae line (529-5921) - preferably by 10:00 AM.

Whole water sample

1. Label 250-mL bottle: location/site, date, time, name of sampler. Record ID # on data sheet. (Formaldehyde:acetic acid solution for preserving is already in bottle – do not discard).
2. Fill bottle with surface water (up to shoulder).
3. Cap bottle and gently roll back and forth to mix preservative and sample.

Vertical Plankton Tow - Subsample to be counted (Sedgewick-Rafter) – procedure on other side

A. Label 60-mL round bottle: location/site, date, time, name of sampler.
B. Slip narrow end of plankton net onto Mason jar (below raised edge), tie securely with attached Velcro fastener.
C. Attach weight to bottom.
D. Lower net towards bottom until the marker on rope indicating 10 m is at the surface of the water.
E. Raise the net gently/slowly through the water and retrieve sample.
F. Drain content of jar back into netting. Rinse sample by pouring seawater from pail onto the outside of the net. Repeat, drain and rinse.
G. Concentrate sample by allowing excess water to drain through mesh.
H. See that jar is filled to the 45-mL line as indicated on jar.
I. Untie plankton net and pour from Mason jar into 60-mL round plastic container. Note: preservative is pre-measured in bottles (do not pour out). Wash Mason jar with seawater.
J. If possible rinse net with fresh water and dry in the dark - OUT OF SUNLIGHT (mesh will degrade if left in sunlight).
K. This sample is to be counted with the Sedgewick Rafter slide – see other side for directions.

Questions:
Phytoplankton: Jennifer Martin (529-5921) or Murielle LeGresley (529-5961)
Sample collection: Simone Tielesh (529-5961) or Paul McCurdy (529-5863)

Using Sedgewick-Rafter slide – from net samples

Appendix 2

Training component

1) Gently invert container 10 times to mix sample thoroughly.
2) Place cover slip on Sedgewick-Rafter (S-R) counting slide leaving a small opening at one end.
3) Using disposable pipette, fill (S-R) slide carefully making sure there are no air bubbles. Close opening with cover slip.
4) Clip (S-R) slide to microscope. Be sure to use 10X objective. Using stage knobs, position slide so you can see the left hand corner of the divided section.
5) Start counting the key species (see species identification guide with pictures). Examine at least one full column of the slide = 20 grid squares. **Note: not all key species will be present in sample**.
6) Record counts on data sheet. Indicate number of grid squares counted.

Please call information from data sheets and Sedgewick-Rafter counts daily to algae line (leave message) at the following number: 529-5921.

Questions:
Phytoplankton: Jennifer Martin (529-5921) or Murielle LeGresley (529-5961)
Sample collection: Simone Tielesh (529-5961) or Paul McCurdy (529-5863)

Appendix 2
Training component

Vertical Plankton tow conversion factors: This is the sample that we have asked that you count.

Table 1. Multiplication factor (MF) for phytoplankton cell counts from a Sedgewick Rafter chamber when a vertical plankton tow was taken.

Example 1: If 20 grid squares were examined and a total of 3 *Alexandrium* sp. cells were counted, then the appropriate MF is 6. The estimated number of cells per litre in the tow will be the MF (6) multiplied by the total number of cells observed (3) in the 20 grid squares resulting in 3×6=18 cells per litre.

Example 2: If 45 grid squares were examined and a total of 7 *Alexandrium* sp. cells were counted, then the appropriate MF is 2.7. The estimated number of cells per litre in the tow will be the MF (2.7) multiplied by the total number of cells observed (7) in the 45 grid squares resulting in 2.7×7=18.9 cells per litre.

Grid Squares	Counted MF	Grid Squares	Counted MF
5	23.9	55	2.2
10	12.0	60	2.0
15	8.0	65	1.8
20	6.0	70	1.7
25	4.8	75	1.6
30	4.0	80	1.5
35	3.4	85	1.4
40	3.0	90	1.3
45	2.7	95	1.3
50	2.4	100	1.2

N.B.: Use of the MF is valid for a 10 m plankton tow concentrated to 45 mL, mixed with 5 mL of preservative and counted using a Sedgewick Rafter chamber. Net diameter is assumed to be 9" (23 cm).

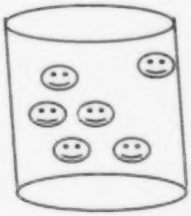
Whole Water Sample: This sample will be counted by DFO from designated sites - not necessary for you to count.

Table 2. Multiplication factor (MF) for phytoplankton cell counts from a Sedgewick Rafter chamber when a whole water sample was taken. The product of the MF and the total number of cells observed is thousands of cells per litre.

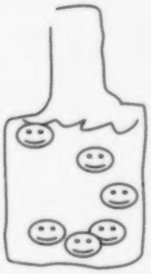
Example: If 25 grid squares were examined, the appropriate MF is 40. If 10 *Alexandrium* sp. cells were observed in those 25 grid squares, then there are estimated to be 10×40=400 thousand *Alexandrium* sp. cells per litre.

Grid Squares	Counted MF	Grid Squares	Counted MF
1	1000	15	67
2	500	20	50
3	333	25	40
4	250	30	33
5	200	35	29
6	167	40	25
7	143	45	22
8	125	50	20
9	111	75	13
10	100	100	10

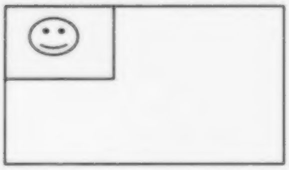
N.B.: Use of the MF is valid for a 1 mL subsample drawn from an unconcentrated preserved whole water sample. Dilution by preservative is not taken into consideration.



Tow volume:
418.146 L



Sample bottle volume:
50 mL



Sedgewick-Rafter slide
volume:
1 mL or 1000 grid cells

Example Calculation

Organisms per slide

1 organism in 100 grid cells
equals
10 organisms in 1000 grid cells

Organisms per bottle

10 organisms on slide (1 mL)
equals
50 x 10 = 500 organisms in 50 mL

Organisms per tow

500 organisms in tow and the tow volume is 418 L.

Therefore there are:
500 organisms in 418 L
equals
500/418 = 1.2 organisms per L

Harmful Phytoplankton Field Data Sheet ID #: **05-MF-** ___

Location/site	**Name of sampler**
Date (mm/dd/yy) / /05	Time (a.m. or p.m.)
Oxygen (%)	Surface water temp. (°C)
Surface whole water **Yes / No**	**Weather/wind & direction**

Fish behaviour (normal, finning, gasping, fish down deep, feeding rates, dying)

Water clarity / visibility:
Other comments:

Counts using Sedgewick-Rafter slide

Species	**Count**	**Number of grid squares counted**
Alexandrium		
Chaetoceros convolutus		
Chaetoceros socialis		
Corethron		
Ditylum		
Eucampia		
Leptocylindrus		
Pseudo-nitzschia		

Please call (529-5921) or leave a message daily with your cell counts. (Preferably by 10 a.m.)

If you have any questions about phytoplankton call:

Jennifer Martin (529-5921) or Murielle LeGresley (529-5961)

Simone Tielesh (529-5961) Paul McCurdy (529-5863) for sample collection

Training in the use of microscopes, identification of phytoplankton, and counting (7 July 2004).

Demonstrating techniques for collecting surface water samples (left) and vertical tows (right) (7 July 2004).

ENHANCED PHYTOPLANKTON MONITORING AT FISH FARMS

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Introduction

The main goal of this project component was the collection of approximately daily sampling of phytoplankton and environmental parameters, as well as the identification and counting of selected algal species at selected participating salmon farms. It was proposed that surface water and vertical tow samples would be taken daily during May through October of 2004 and 2005 at four to six locations in southwestern New Brunswick (SWNB). The number of locations would depend on the number of participating companies. In addition, it was proposed that DFO scientists would conduct occasional 12- to 13-h periods of intensive sampling at selected farms and times. This high frequency sampling was to be used to test the hypothesis that the onset of a phytoplankton bloom in an area could be detected and forecasted by daily phytoplankton monitoring at the farms.

Methods

In 2004, there were four participating companies and four enhanced monitoring sites. It was originally proposed to have sites in Passamaquoddy Bay and in the Grand Manan Island area in 2004; however, we could not use sites in Passamaquoddy Bay in 2004, because no farms were operating in this area due to an outbreak of infectious salmon anemia (ISA). Consequently, all four enhanced monitoring sites in 2004 were in the Grand Manan Island area (sites 002, 172, 368, and 403; see Fig. 1). In 2005, there also were four enhanced monitoring sites (Fig. 1), with two in the Grand Manan Island area (sites 172 and 292), one in Passamaquoddy Bay (site 377) and one on the mainland shore (site 378). One site (172) was monitored in both years. Because of some delays in initiating the project, enhanced monitoring did not start until early July in 2004. In 2005, monitoring started in late May.

Water samples were collected by workers at the participating farms. Surface water (250 mL) and vertical tow (from 10 m depth to surface) samples were taken. One set of samples was preserved for later examination by DFO phytoplankton experts (J.L. Martin and M.M. LeGresley). The other set of samples was to be examined on site by the industry partners using standardized equipment and examination protocols (field microscope, standardized sample preparation, etc.). Farm workers were asked to analyze only the vertical tow samples; however, some surface water samples were also analyzed by farm staff. The identified species and counts of abundance were recorded by the farm workers and reported to the DFO researchers. See Appendix 2 for details on sampling and counting methods.

The species chosen for identification and enumeration from water samples included species known to cause problems in SWNB salmon farms, or in salmon farms in other geographical areas and also known to exist in SWNB (Martin et al. 2001). The following species were chosen: *Alexandrium fundyense*, *Chaetoceros convolutus*, *C. socialis*, *Corethron criophilum*, *Ditylum* *brightwellii, Eucampia zodiacus, Leptocylindrus minimus, Mesodinium rubrum*, the *Pseudo-nitzschia delicatissima* group (includes *P. delicatissima and P. pseudodelicatissima*) and the *P. seriata* group (includes *P. seriata, P. subpacifica, P. multiseries, P. pungens*, and *P. fraudulenta*, which are difficult to positively identify using a compound microscope). Another species, *Membraneis challengeri*, which had not previously been observed in SWNB, was included after it was observed in relatively high numbers in 2005.

Counts were recorded as organisms per litre, with an organism defined as a cell (for species normally occurring as individual cells, such as *Alexandrium, Ditylum, Membraneis, Mesodinium*) or a chain (for species normally occurring as chains of cells, such as *Chaetoceros, Eucampia, Leptocylindrus, Pseudo-nitzschia*).

DFO researchers also conducted one 12-h sampling event, with surface water samples (for phytoplankton analyses) taken every 3-4 h during daylight hours, along with hourly recording of temperature and dissolved oxygen levels.

Results

Water temperatures were recorded by farm workers at the time of sample collection. In both years the water temperature showed a general increase during the sampling season, ranging from 7.1-12.1°C in 2004 and 5.6-13.4°C in 2005 (Fig. 2). In 2005, temperatures were higher at the Passamaquoddy Bay site (377) during mid-July to mid-September, compared to the three other sites. At the one site which was sampled in both years (farm 172), temperatures in early July appeared to be lower in 2004 than in 2005, but there was no clear difference between years in August-September (Fig. 3).

Dissolved oxygen levels were recorded by farm workers much less frequently (Fig. 4). Only one farm (172) reported any dissolved oxygen data in 2004 and that was only on 7 d. Three farms reported some dissolved oxygen data in 2005. For two of these farms (292 and 378), the levels remained within a fairly narrow range, between 8.5-11.1 mg·L^{-1}. The other farm (172) reported dissolved oxygen levels from 7.4-15.2 mg·L^{-1} (83-141% saturation), with a peak in late July 2005 and lowest values in early August 2005.

The number of samples collected was substantially higher in 2005 than in 2004 (Table 1, Fig. 5). This was partly because sampling started earlier in the year in 2005, but also because sampling was more frequent in 2005. In 2004, the four farms collected a total of 193 surface water samples and 186 vertical tow samples between July and September. The range in the number of samples collected per farm in 2004 was 21-66 for surface water samples and 15-64 for vertical tow samples. These represent 27-97% of the potential number of surface water samples and 19-94% of vertical tow samples (100% would mean samples were collected every day between the first and last days of sampling at the site). In 2005, the four farms collected a total of 308 surface water samples and 304 vertical tow samples between late May and September. The range in the number of samples collected per farm in 2005 was 50-93 for surface water samples and 45-93 for vertical tow samples. These represent 57-94% of the potential number of surface water samples and 51-94% of the potential number of vertical tow samples.

Appendix 3

Enhanced phytoplankton monitoring

Phytoplankton identification and counting by farm staff were done for only a small fraction of the collected samples (Table 2, Fig. 5). In 2004, the numbers of daily count forms submitted ranged from 0-9 per farm for surface water samples and 0-12 for vertical tow samples. These represent only 0-12% of the potential number of surface water samples and 0-20% of the potential number of vertical tow samples (100% would mean counts were submitted for every day between the first and last days of sampling at the site). There were no surface water or vertical tow counts submitted by site 002 and no surface water counts by site 368. The only species counted on a regular basis by farm workers in 2004 was *A. fundyense*.

In 2005, the numbers of daily count forms submitted ranged from 0-36 per farm for surface water samples and 0-23 for vertical tow samples. These represent 0-41% of the potential number of surface water samples and 0-26% of the potential number of vertical tow samples, which were improvements over 2004, but were still low. The 2005 farm worker counts of vertical tows at sites 292, 377, and 378 included several species (there were no vertical tow counts submitted by site 172). In the 2005 farm worker counts of surface water samples, only site 378 recorded several species; workers at site 172 counted only *M. challengeri*, workers at site 377 counted only *M. rubrum*, and there were no surface water counts by workers at site 292.

DFO counts were only done for three surface water samples (and no vertical tows) at site 002 in 2004 (there were no farm worker counts at this site). The species showing the highest abundance in these samples was the *P. delicatissima* group (Table 3, Fig. 6). For the other three sites sampled in 2004, there were similar abundance patterns among the sites for the most common species, with the highest abundances at site 368. The most abundant species at sites 172, 368, and 403 were *A. fundyense* and the *P. delicatissima* group (Tables 3 and 4; Fig. 6, 7, and 8). *A. fundyense* was more abundant in July and early August, with lower abundance in late August and September. The other common species did not show clear seasonal patterns during the sampling period. The only species that reached historical maximum bloom levels (see Appendix 4) in 2004 were *A. fundyense* at sites 172 and 368, and the *P. delicatissima* group at site 002. Abundance levels were higher in surface water samples than in vertical haul samples. There were no counts of *M. rubrum* in vertical tow counts, because this species is fragile and most cells were damaged in vertical tows.

As previously mentioned, *A. fundyense* was the only species that farm workers identified and counted on a regular basis in 2004. Where farm worker counts and DFO counts were done on approximately the same dates, the values were relatively close, except at site 172 where the two farm counts of surface water samples did not detect any cells of this species, while DFO counts at approximately the same days detected in the order of 100 organisms$\cdot$L^{-1}.

There was more variability among sites in 2005, than in 2004. The abundance of most species was highest at site 377. The species showing the highest abundance at each site in 2005 were: at sites 172 and 292, the *P. delicatissima* group and *M. challengeri*; at site 377, the *P. delicatissima* group, *L. minimus*, *M. rubrum*, *C. socialis*, and *A. fundyense*; and at site 378, *A. fundyense*, the *P. delicatissima* group, *M. challengeri*, and *M. rubrum* (Fig. 9).

Abundance data for the most common species in 2005 are shown in Table 5 and Fig. 10 (surface water samples) and in Table 6 and Fig. 11 (vertical tow samples). *A. fundyense* was most abundant at farms 377 and 378, with relatively low numbers at the other two sites; abundance was highest in June-July. *C. convolutus* and *C. socialis* were most abundant at site 377. *C. convolutus* was most abundant in June-July, and was absent in August, while *C. socialis* was most abundant in July-August. *L. minimus* also showed highest abundance at site 377; this species showed two peaks in abundance, in late June and in August. *M. challengeri* showed similar abundance trends at all four sites, with highest abundance in July and early August. *M. rubrum* was most abundant at sites 377 and 378. The *P. delicatissima* group was most abundant at site 377 and showed relatively high abundance at site 172; this species showed two peaks in abundance, in late June and in late August. The only species that reached historical maximum bloom levels (see Appendix 4) in 2005 were *M. rubrum*, in farm counts at site 377, and the *P. delicatissima* group, in DFO counts at site 377. As in 2004, abundance levels in 2005 were higher in surface water samples than in vertical haul samples.

In general, farm worker counts and DFO counts showed similar seasonal trends in abundance in 2005. However, the highest numbers counted by farm workers were often higher than corresponding DFO counts, and for many of the species (other than *A. fundyense*), the farm workers often reported no organisms present on days when they were detected in DFO analyses. In the vertical tow counts of *M. challengeri* at site 378 in early July 2005, the farm worker counts were up to 258 organisms·L^{-1}, while DFO analyses reported no presence of this species. In vertical tow samples taken later in July 2005 at this site, the farm worker and DFO counts for this species were a close match: farm counts for the 21 July and 30 July samples were 147 and 349 organisms·L^{-1}, respectively, while DFO counts were 255 and 452 organisms·L^{-1}.

Some differences in species abundance were noted between the two sampling years. *A. fundyense, C. criophilum*, the *P. delicatissima* group, and the *P. seriata* group were more abundant in 2004 than in 2005. *C. socialis, L. minimus*, and *M. rubrum* were most abundant at one site (377) in 2005. *M. challengeri* was observed in low numbers in 2004 (but not recorded), but was abundant at all four sites in 2005. At the one site (172) which was monitored in both years, *A. fundyense, C. convolutus, C. socialis, C. criophilum, M. rubrum*, and the *P. seriata* group were more abundant in 2004; *Eucampia zodiacus, M. challengeri*, and the *P. delicatissima* group were more abundant in 2005; and the other species showed similar levels in both years.

One 12-h intensive sampling event was conducted at farm 002 on 23 September 2004, from 09:00 to 19:00 Atlantic Daylight Time. Temperature and dissolved oxygen levels remained constant throughout the sampling period (Fig. 12). Water temperature averaged 11.1°C (range: 10-7-11.7°C) and dissolved oxygen averaged 9.3 mg·L^{-1} (range: 8.9-9.7 mg·L^{-1}). The abundance of phytoplankton was low, with no clear temporal trends during the sampling period (Fig. 12). The most abundant species was the *P. delicatissima* group. No further 12-h sampling events were conducted.

Discussion

The frequency of sample collection by farm staff was relatively high (61-64% of potential daily samples in 2004; 75-76% in 2005). However the frequency of sample identification and counting was much lower: counts were submitted for only 4-8% of the potential daily counts in 2004, and 11-13% in 2005). Some of the reasons for the low frequency of sample counts included: farm staff had to do many other tasks with higher priorities; phytoplankton identification and counting were more tedious and required much more time than sample collection; there were few phytoplankton blooms at any of the enhanced monitoring sites during the project, so interest in examining the samples may have waned; and in some cases, the microscopes were transferred to other farms which were experiencing phytoplankton problems. It should be noted that some companies implemented phytoplankton monitoring programs at some of their farms which were not part of this project, especially where there were suspicions of phytoplankton problems.

The similar patterns of abundance of species among the four sites sampled in 2004 was not surprising, because all four enhanced monitoring sites were in the Grand Manan Island area and hence were not widely separated geographically. The four sites sampled in 2005 were more widely separated and there was more variability in species abundances among sites in that year.

The abundance of phytoplankton was higher in surface water samples than in the vertical tows. This was because most species were usually more abundant close to the surface, while the vertical tow abundance data represented average concentrations over the depth of the tow (approximately 0-11 m depth).

A. fundyense and the *P. delicatissima* group were the most abundant species in both years, with both showing higher levels in 2004, than in 2005. Farmed salmon mortalities attributed to algal blooms were not reported at any of the enhanced monitoring sites in either year. However, elevated salmon mortality levels believed to be attributable to *A. fundyense* were reported by several farms in SWNB in 2004, in Lime Kiln Bay, Bliss Harbour, and Beaver Harbour. In Beaver Harbour, *A. fundyense* levels >3 000 000 organisms·L^{-1} were reported (the maximum reported in our study sites was 556 000 organisms·L^{-1} at site 368). There were also reports of elevated paralytic shellfish poisoning (PSP) toxins in clams and mussels in SWNB in 2004. For comparison, in the mid-1990s, the maximum concentrations of *A. fundyense* in SWNB were 5 000-10 000 organisms·L^{-1} (Page et al. 2006), while in September 2003, when high numbers of salmon mortalities were occurring at farms in the eastern Grand Manan Island area, concentrations reached 890 000 organisms·L^{-1} (Martin et al. 2006a). The *P. delicatissima* group attained very high levels (up to 1.5 million organisms·L^{-1} at site 377 in 2005), but this did not appear to be associated with any problems at this farm.

There was insufficient dissolved oxygen data recorded to allow us to determine if there was any clear relationship between oxygen levels and phytoplankton blooms. However, high dissolved oxygen levels at site 172 in July 2005 (reaching 15.2 mg·L^{-1} or 141% saturation) were concurrent with a bloom of *M. challengeri* (up to 30 000 organisms·L^{-1} in farm worker counts). Because this species is quite large, it may have a relatively large influence (on a per organism basis) on dissolved oxygen levels. This species is new to this area, having been observed for the first time in SWNB in 2004. Abundance in that year was low and it was not included among the species for which counts were recorded. Because of its increased abundance in 2005, this species was added to the list of species to be counted.

The low frequency of phytoplankton counts by farms, together with the relatively low abundance of most species, meant that there was not sufficient data to provide enough time series which could be statistically analyzed to determine if there is predictive power in the enhanced monitoring data. The farm-collected data could, however, allow farms to confirm if phytoplankton blooms were occurring when there were suspicions that bloom events were impacting or approaching their farms, thus triggering increased frequency of monitoring. The phytoplankton counts could also be used to determine when levels were sufficiently high (based on the results of studies on the threshold concentrations causing harm to farmed salmon, and on observations of the relationship between phytoplankton counts and fish health problems at other farms or in other years) to warrant management decisions, such as to stop feeding or initiate early harvesting (Martin et al. 2006b).

References

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Appendix 3
Enhanced phytoplankton monitoring

Table 1. Numbers of samples collected at enhanced monitoring sites. For the percent of potential samples, 100% would indicate that samples were collected every day from the first sampling date to the last sampling date in the year. Numbers are ranges for the four sites sampled in each year; numbers in parentheses are means.

	Surface samples	Vertical tows
2004 (July-September)		
Number of samples collected	21 – 66 (48.3)	15 – 64 (46.5)
% of potential number of samples	26.6 – 97.1 (63.6)	19.0 – 94.1 (61.2)
2005 (May-September)		
Number of samples collected	50 – 93 (77.0)	45 – 93 (76.0)
% of potential number of samples	56.8 – 93.9 (76.0)	51.1 – 93.9 (75.0)

Table 2. Numbers of samples for which phytoplankton species counts were submitted by enhanced monitoring sites. For the percent of potential samples, 100% would indicate that sample counts were done every day from the first sampling date to the last sampling date in the year. Numbers are ranges for the four sites sampled in each year; numbers in parentheses are means.

	Surface samples	Vertical tows
2004 (July-September)		
Number of samples counted	0 – 9 (3.3)	0 – 17 (6.3)
% of potential number of samples	0 – 12.0 (4.3)	0 – 20.7 (8.3)
2005 (May-September)		
Number of samples counted	0 – 36 (11.3)	0 – 23 (13.3)
% of potential number of samples	0 – 40.9 (11.2)	0 – 26.1 (13.1)

Appendix 3

Enhanced phytoplankton monitoring

Table 3. Summary table of phytoplankton species counts in surface water samples collected at the four enhanced monitoring sites in 2004. For farm 002, DFO counts were only done for three samples taken in September and there were no counts by farm staff.

Farm	Species	Analyzed by	n	Organisms per L		
				Mean	Minimum	Maximum
002	*Alexandrium fundyense*	DFO	3	373	0	560
002	*Chaetoceros convolutus*	DFO	3	279	120	578
002	*Chaetoceros socialis*	DFO	3	47	0	140
002	*Corethron criophilum*	DFO	3	320	0	720
002	*Ditylum brightwellii*	DFO	3	293	0	720
002	*Eucampia zodiacus*	DFO	3	13	0	40
002	*Leptocylindrus minimus*	DFO	3	387	0	720
002	*Mesodinium rubrum*	DFO	3	425	0	1 156
002	*Pseudo-nitzschia delicatissima*	DFO	3	1 199 823	167 620	2 955 900
002	*Pseudo-nitzschia seriata*	DFO	3	1 762	520	4 046
172	*Alexandrium fundyense*	DFO	18	10 979	0	98 812
172	*Alexandrium fundyense*	Farm	2	0	0	0
172	*Chaetoceros convolutus*	DFO	18	168	0	578
172	*Chaetoceros socialis*	DFO	18	69	0	640
172	*Corethron criophilum*	DFO	18	28	0	320
172	*Ditylum brightwellii*	DFO	18	4	0	60
172	*Eucampia zodiacus*	DFO	18	24	0	160
172	*Leptocylindrus minimus*	DFO	18	440	0	1 740
172	*Mesodinium rubrum*	DFO	18	700	0	2 890
172	*Pseudo-nitzschia delicatissima*	DFO	18	16 865	160	60 690
172	*Pseudo-nitzschia seriata*	DFO	18	73	0	340
368	*Alexandrium fundyense*	DFO	18	61 769	0	555 917
368	*Chaetoceros convolutus*	DFO	18	105	0	289
368	*Chaetoceros socialis*	DFO	18	163	0	1 360
368	*Corethron criophilum*	DFO	18	52	0	200
368	*Ditylum brightwellii*	DFO	18	64	0	700
368	*Eucampia zodiacus*	DFO	18	14	0	240
368	*Leptocylindrus minimus*	DFO	18	394	0	2 600
368	*Mesodinium rubrum*	DFO	18	1 180	80	4 046
368	*Pseudo-nitzschia delicatissima*	DFO	18	27 240	260	177 446
368	*Pseudo-nitzschia seriata*	DFO	18	58	0	240
403	*Alexandrium fundyense*	DFO	18	1 192	0	8 140
403	*Alexandrium fundyense*	Farm	9	2 167	0	15 000
403	*Chaetoceros convolutus*	DFO	18	29	0	160
403	*Chaetoceros socialis*	DFO	18	38	0	480
403	*Corethron criophilum*	DFO	18	8	0	80
403	*Ditylum brightwellii*	DFO	18	7	0	40
403	*Eucampia zodiacus*	DFO	18	13	0	40
403	*Leptocylindrus minimus*	DFO	18	118	0	820
403	*Mesodinium rubrum*	DFO	18	462	40	1 180
403	*Pseudo-nitzschia delicatissima*	DFO	18	2 778	520	11 960
403	*Pseudo-nitzschia seriata*	DFO	18	10	0	100

Appendix 3
Enhanced phytoplankton monitoring

Table 4. Summary table of phytoplankton species counts in vertical tow samples collected at three enhanced monitoring sites in 2004. There were no counts of vertical tow samples from the fourth farm (002).

Farm	Species	Analyzed by	n	Organisms per L Mean	Organisms per L Minimum	Organisms per L Maximum
172	*Alexandrium fundyense*	DFO	10	60	0	329
172	*Alexandrium fundyense*	Farm	3	8	0	19
172	*Chaetoceros convolutus*	DFO	10	<1	0	1
172	*Chaetoceros socialis*	DFO	10	1	0	14
172	*Corethron criophilum*	DFO	10	0	0	0
172	*Ditylum brightwellii*	DFO	10	0	0	0
172	*Eucampia zodiacus*	DFO	10	0	0	0
172	*Leptocylindrus minimus*	DFO	10	0	0	0
172	*Pseudo-nitzschia delicatissima*	DFO	10	21	0	98
172	*Pseudo-nitzschia seriata*	DFO	10	<1	0	2
368	*Alexandrium fundyense*	DFO	7	491	72	2 364
368	*Alexandrium fundyense*	Farm	17	381	50	2 628
368	*Chaetoceros convolutus*	DFO	7	2	0	12
368	*Chaetoceros socialis*	DFO	7	0	0	0
368	*Corethron criophilum*	DFO	7	0	0	0
368	*Ditylum brightwellii*	DFO	7	<1	0	1
368	*Eucampia zodiacus*	DFO	7	1	0	5
368	*Leptocylindrus minimus*	DFO	7	3	0	18
368	*Pseudo-nitzschia delicatissima*	DFO	7	1 553	0	7 368
368	*Pseudo-nitzschia seriata*	DFO	7	10	0	44
403	*Alexandrium fundyense*	DFO	9	168	0	859
403	*Alexandrium fundyense*	Farm	5	89	0	282
403	*Chaetoceros convolutus*	DFO	9	1	0	5
403	*Chaetoceros socialis*	DFO	9	0	0	0
403	*Corethron criophilum*	DFO	9	0	0	0
403	*Ditylum brightwellii*	DFO	9	0	0	0
403	*Eucampia zodiacus*	DFO	9	<1	0	1
403	*Leptocylindrus minimus*	DFO	9	1	0	6
403	*Pseudo-nitzschia delicatissima*	DFO	9	46	0	214
403	*Pseudo-nitzschia seriata*	DFO	9	<1	0	2

Table 5. Summary table of phytoplankton species counts in surface water samples collected at the four enhanced monitoring sites in 2005.

		Analyzed	Organisms per L			
Farm	Species	by	n	Mean	Minimum	Maximum
172	*Alexandrium fundyense*	DFO	10	468	0	1 400
172	*Chaetoceros convolutus*	DFO	10	32	0	120
172	*Chaetoceros socialis*	DFO	10	4	0	40
172	*Corethron criophilum*	DFO	10	0	0	0
172	*Ditylum brightwellii*	DFO	10	0	0	0
172	*Eucampia zodiacus*	DFO	10	60	0	560
172	*Leptocylindrus minimus*	DFO	10	388	0	1 440
172	*Membraneis challengeri*	DFO	10	3 856	0	20 360
172	*Membraneis challengeri*	Farm	4	20 000	10 000	30 000
172	*Mesodinium rubrum*	DFO	10	328	0	600
172	*Pseudo-nitzschia delicatissima*	DFO	10	25 936	0	120 800
172	*Pseudo-nitzschia seriata*	DFO	10	4	0	40
292	*Alexandrium fundyense*	DFO	12	273	0	1 080
292	*Chaetoceros convolutus*	DFO	12	40	0	160
292	*Chaetoceros socialis*	DFO	12	0	0	0
292	*Corethron criophilum*	DFO	12	0	0	0
292	*Ditylum brightwellii*	DFO	12	3	0	40
292	*Eucampia zodiacus*	DFO	12	7	0	80
292	*Leptocylindrus minimus*	DFO	12	93	0	240
292	*Membraneis challengeri*	DFO	12	1 840	0	17 320
292	*Mesodinium rubrum*	DFO	12	833	0	2 720
292	*Pseudo-nitzschia delicatissima*	DFO	12	3 477	0	9 920
292	*Pseudo-nitzschia seriata*	DFO	12	0	0	0
377	*Alexandrium fundyense*	DFO	7	4 497	0	20 320
377	*Chaetoceros convolutus*	DFO	7	337	0	1 800
377	*Chaetoceros socialis*	DFO	7	5 457	0	27 200
377	*Corethron criophilum*	DFO	7	0	0	0
377	*Ditylum brightwellii*	DFO	7	11	0	80
377	*Eucampia zodiacus*	DFO	7	86	0	240
377	*Leptocylindrus minimus*	DFO	7	10 360	40	45 760
377	*Membraneis challengeri*	DFO	7	994	0	6 640
377	*Mesodinium rubrum*	DFO	7	7 274	40	44 520
377	*Mesodinium rubrum*	Farm	21	20 857	0	225 000
377	*Pseudo-nitzschia delicatissima*	DFO	7	397 811	0	1 469 600
377	*Pseudo-nitzschia seriata*	DFO	7	74	0	480

Table 5 (continued).

Farm	Species	Analyzed by	Organisms per L			
			n	Mean	Minimum	Maximum
378	*Alexandrium fundyense*	DFO	27	7 289	0	41 040
378	*Alexandrium fundyense*	Farm	36	27 639	0	160 000
378	*Chaetoceros convolutus*	DFO	27	31	0	280
378	*Chaetoceros convolutus*	Farm	36	139	0	5 000
378	*Chaetoceros socialis*	DFO	27	16	0	240
378	*Chaetoceros socialis*	Farm	36	0	0	0
378	*Corethron criophilum*	DFO	27	0	0	0
378	*Corethron criophilum*	Farm	36	0	0	0
378	*Ditylum brightwellii*	DFO	27	4	0	40
378	*Ditylum brightwellii*	Farm	36	0	0	0
378	*Eucampia zodiacus*	DFO	27	3	0	40
378	*Eucampia zodiacus*	Farm	36	0	0	0
378	*Leptocylindrus minimus*	DFO	27	114	0	760
378	*Leptocylindrus minimus*	Farm	36	417	0	15 000
378	*Membraneis challengeri*	DFO	27	1 864	0	20 800
378	*Membraneis challengeri*	Farm	36	3 750	0	55 000
378	*Mesodinium rubrum*	DFO	27	1 137	0	9 240
378	*Mesodinium rubrum*	Farm	36	1 528	0	20 000
378	*Pseudo-nitzschia delicatissima*	DFO	27	2 474	0	20 800
378	*Pseudo-nitzschia delicatissima*	Farm	36	0	0	0
378	*Pseudo-nitzschia seriata*	DFO	27	10	0	200
378	*Pseudo-nitzschia seriata*	Farm	36	0	0	0

Table 6. Summary table of phytoplankton species counts in vertical tow samples collected at the four enhanced monitoring sites in 2005.

		Analyzed		Organisms per L		
Farm	Species	by	n	Mean	Minimum	Maximum
172	*Alexandrium fundyense*	DFO	88	3	0	30
172	*Chaetoceros convolutus*	DFO	88	<1	0	1
172	*Chaetoceros socialis*	DFO	88	<1	0	2
172	*Corethron criophilum*	DFO	88	<1	0	0
172	*Ditylum brightwellii*	DFO	88	<1	0	40
172	*Eucampia zodiacus*	DFO	88	<1	0	40
172	*Leptocylindrus minimus*	DFO	88	2	0	96
172	*Membraneis challengeri*	DFO	88	29	0	668
172	*Pseudo-nitzschia delicatissima*	DFO	88	23	0	595
172	*Pseudo-nitzschia seriata*	DFO	88	<1	0	7
292	*Alexandrium fundyense*	DFO	156	4	0	89
292	*Alexandrium fundyense*	Farm	9	41	1	120
292	*Chaetoceros convolutus*	DFO	156	1	0	88
292	*Chaetoceros convolutus*	Farm	9	<1	0	1
292	*Chaetoceros socialis*	DFO	156	1	0	88
292	*Chaetoceros socialis*	Farm	9	0	0	0
292	*Corethron criophilum*	DFO	156	1	0	88
292	*Corethron criophilum*	Farm	9	0	0	0
292	*Ditylum brightwellii*	DFO	156	2	0	89
292	*Ditylum brightwellii*	Farm	9	0	0	0
292	*Eucampia zodiacus*	DFO	156	1	0	88
292	*Eucampia zodiacus*	Farm	9	0	0	0
292	*Leptocylindrus minimus*	DFO	156	4	0	96
292	*Leptocylindrus minimus*	Farm	9	0	0	0
292	*Membraneis challengeri*	DFO	156	94	0	3 101
292	*Membraneis challengeri*	Farm	9	694	0	1 968
292	*Pseudo-nitzschia delicatissima*	DFO	156	55	0	1 518
292	*Pseudo-nitzschia delicatissima*	Farm	9	6	0	54
292	*Pseudo-nitzschia seriata*	DFO	156	1	0	88
292	*Pseudo-nitzschia seriata*	Farm	9	0	0	0

Table 6 (continued).

Farm	Species	Analyzed by	n	Organisms per L		
				Mean	Minimum	Maximum
377	*Alexandrium fundyense*	DFO	149	14	0	174
377	*Alexandrium fundyense*	Farm	21	65	6	246
377	*Chaetoceros convolutus*	DFO	149	2	0	156
377	*Chaetoceros convolutus*	Farm	21	17	0	336
377	*Chaetoceros socialis*	DFO	149	1 251	0	38 671
377	*Chaetoceros socialis*	Farm	21	0	0	0
377	*Corethron criophilum*	DFO	149	2	0	156
377	*Corethron criophilum*	Farm	21	0	0	0
377	*Ditylum brightwellii*	DFO	149	3	0	156
377	*Ditylum brightwellii*	Farm	21	0	0	0
377	*Eucampia zodiacus*	DFO	149	2	0	156
377	*Eucampia zodiacus*	Farm	21	0	0	0
377	*Leptocylindrus minimus*	DFO	149	16	0	1 200
377	*Leptocylindrus minimus*	Farm	21	0	0	0
377	*Membraneis challengeri*	DFO	149	125	0	3 101
377	*Membraneis challengeri*	Farm	21	0	0	0
377	*Pseudo-nitzschia delicatissima*	DFO	149	511	0	24 720
377	*Pseudo-nitzschia delicatissima*	Farm	21	0	0	0
377	*Pseudo-nitzschia seriata*	DFO	149	6	0	156
377	*Pseudo-nitzschia seriata*	Farm	21	0	0	0
378	*Alexandrium fundyense*	DFO	41	93	0	488
378	*Alexandrium fundyense*	Farm	23	175	14	492
378	*Chaetoceros convolutus*	DFO	41	1	0	8
378	*Chaetoceros convolutus*	Farm	23	2	0	24
378	*Chaetoceros socialis*	DFO	41	<1	0	12
378	*Chaetoceros socialis*	Farm	23	0	0	0
378	*Corethron criophilum*	DFO	41	<1	0	1
378	*Corethron criophilum*	Farm	23	<1	0	1
378	*Ditylum brightwellii*	DFO	41	<1	0	1
378	*Ditylum brightwellii*	Farm	23	<1	0	2
378	*Eucampia zodiacus*	DFO	41	0	0	0
378	*Eucampia zodiacus*	Farm	23	<1	0	1
378	*Leptocylindrus minimus*	DFO	41	1	0	10
378	*Leptocylindrus minimus*	Farm	23	<1	0	7
378	*Membraneis challengeri*	DFO	41	39	0	451
378	*Membraneis challengeri*	Farm	23	47	0	348
378	*Pseudo-nitzschia delicatissima*	DFO	41	17	0	330
378	*Pseudo-nitzschia delicatissima*	Farm	23	0	0	0
378	*Pseudo-nitzschia seriata*	DFO	41	<1	0	6
378	*Pseudo-nitzschia seriata*	Farm	23	0	0	0

Appendix 3
Enhanced phytoplankton monitoring

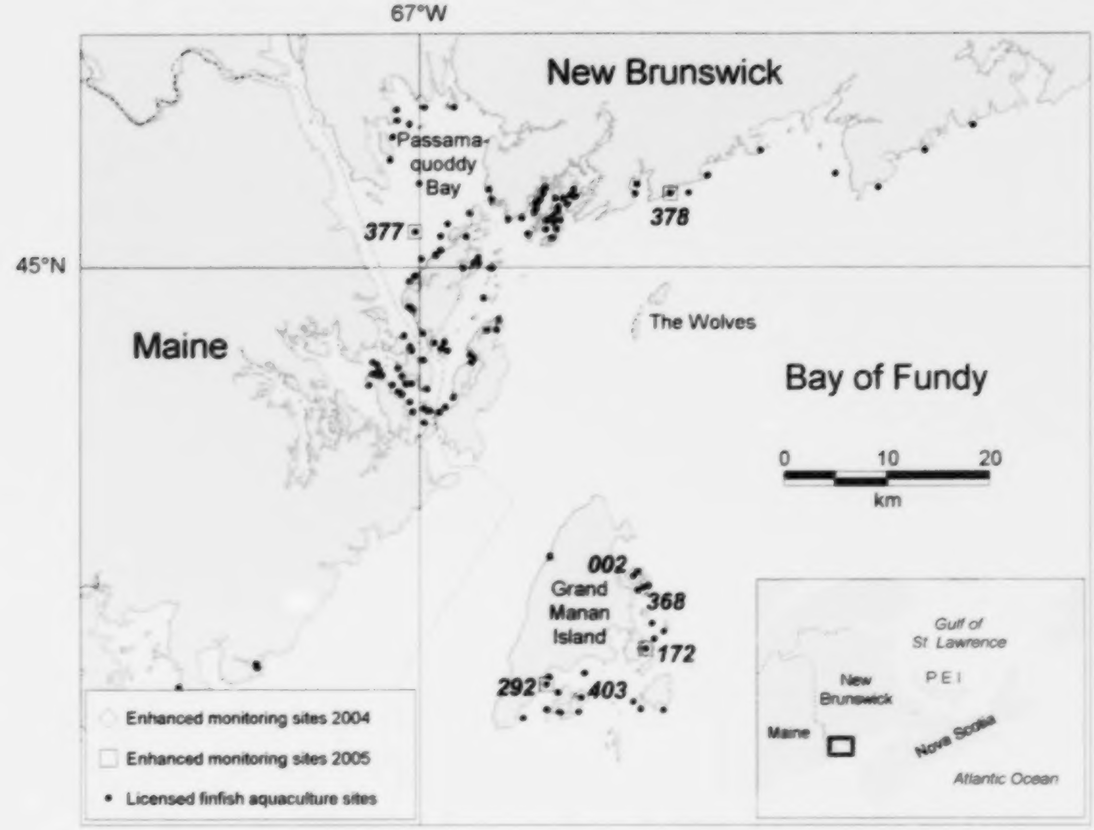
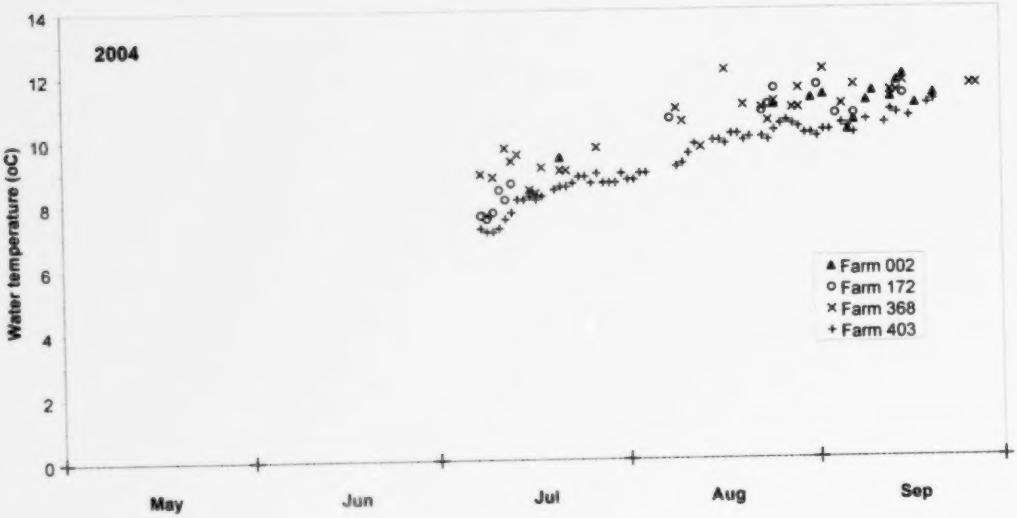

67°W
45°N
New Brunswick
Passamaquoddy Bay
377
378
The Wolves
Maine
Bay of Fundy
0
10
20
km
002
368
172
292
403
Grand Manan Island
Enhanced monitoring sites 2004
Enhanced monitoring sites 2005
Licensed finfish aquaculture sites
Gulf of St. Lawrence
P.E.I.
New Brunswick
Maine
Nova Scotia
Atlantic Ocean

Fig. 1. Map of the SWNB area showing enhanced phytoplankton monitoring sites in 2004 and 2005. Four sites were monitored in each year: sites 002, 172, 368, and 403 (all in the Grand Manan Island area) in 2004, and sites 172, 292, 377, and 378 in 2005 (site 172 was monitored in both years).

Appendix 3
Enhanced phytoplankton monitoring



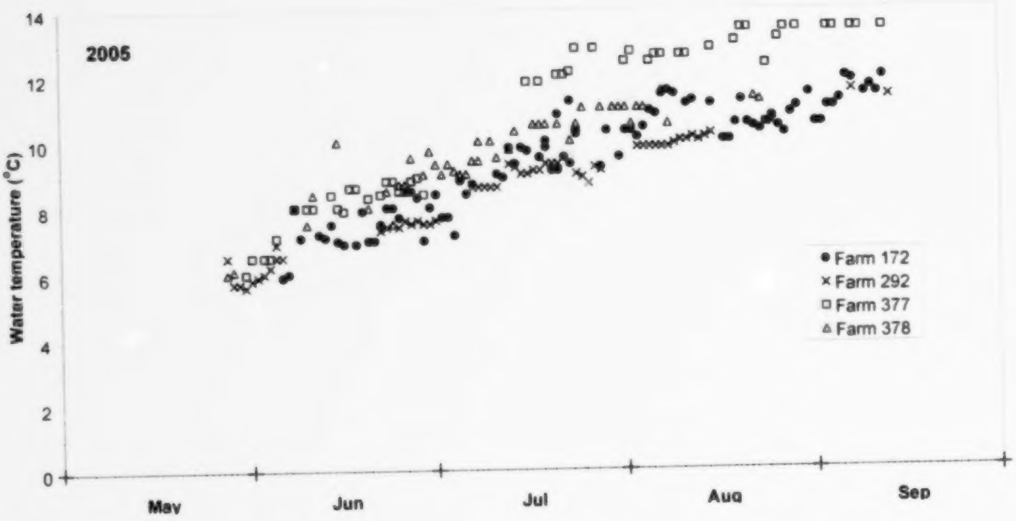


Fig. 2. Surface water temperatures at enhanced monitoring sites in 2004 (top) and 2005 (bottom).

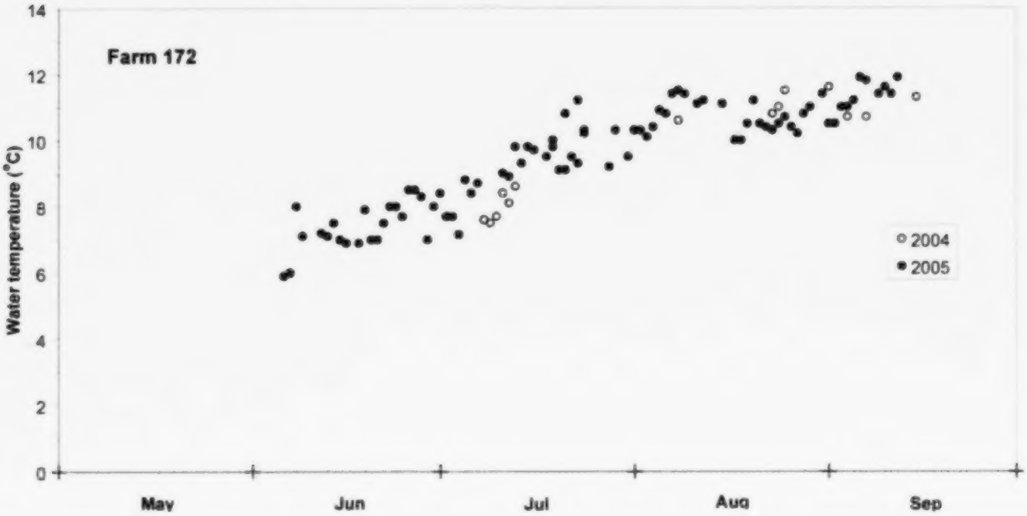


Fig. 3. Surface water temperature data collected at farm 172 in 2004 and 2005.

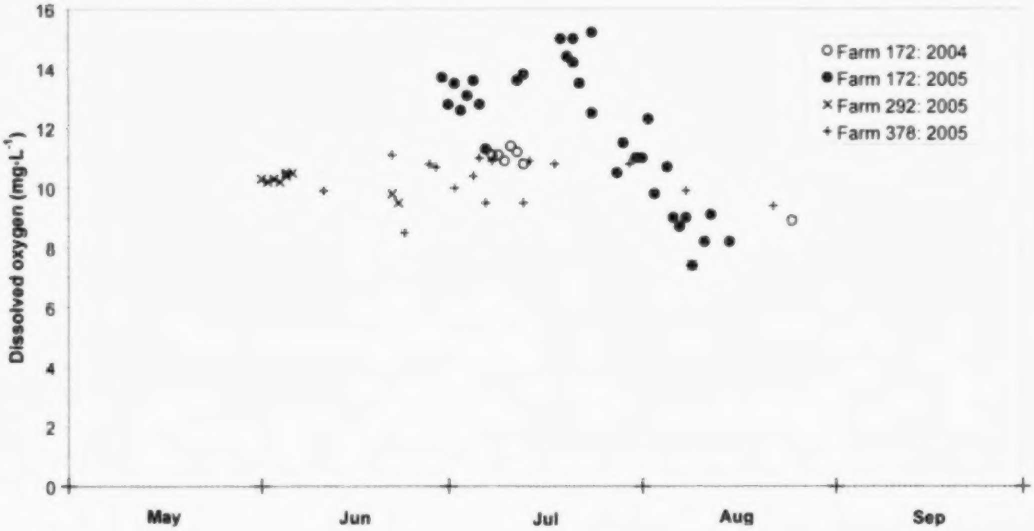


Fig. 4. Dissolved oxygen levels in surface water collected at enhanced monitoring sites in 2004 and 2005.

Appendix 3

Enhanced phytoplankton monitoring

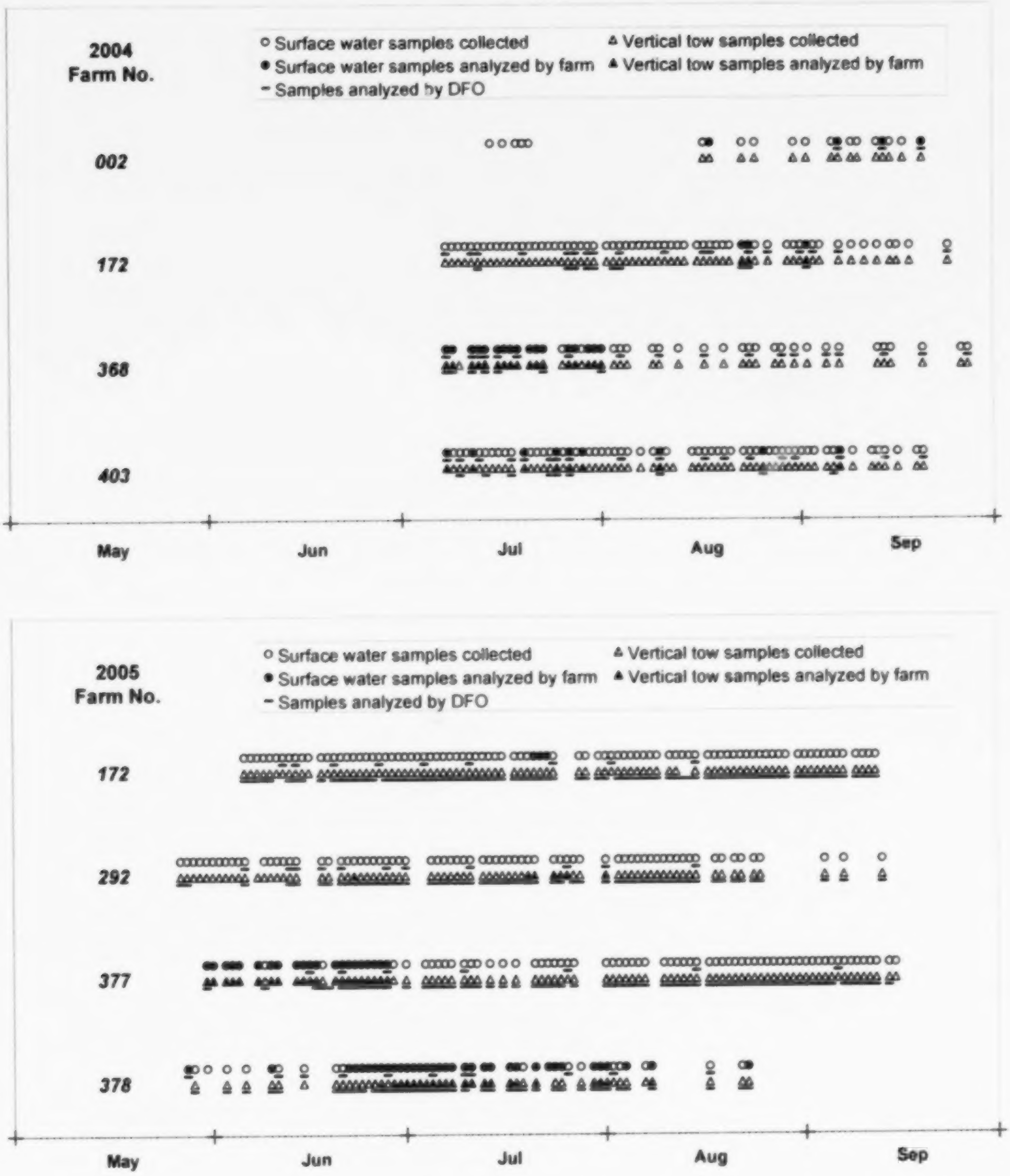


Fig. 5. Charts showing the frequency of phytoplankton sampling and analysis at the four enhanced monitoring sites in 2004 (top) and 2005 (bottom).

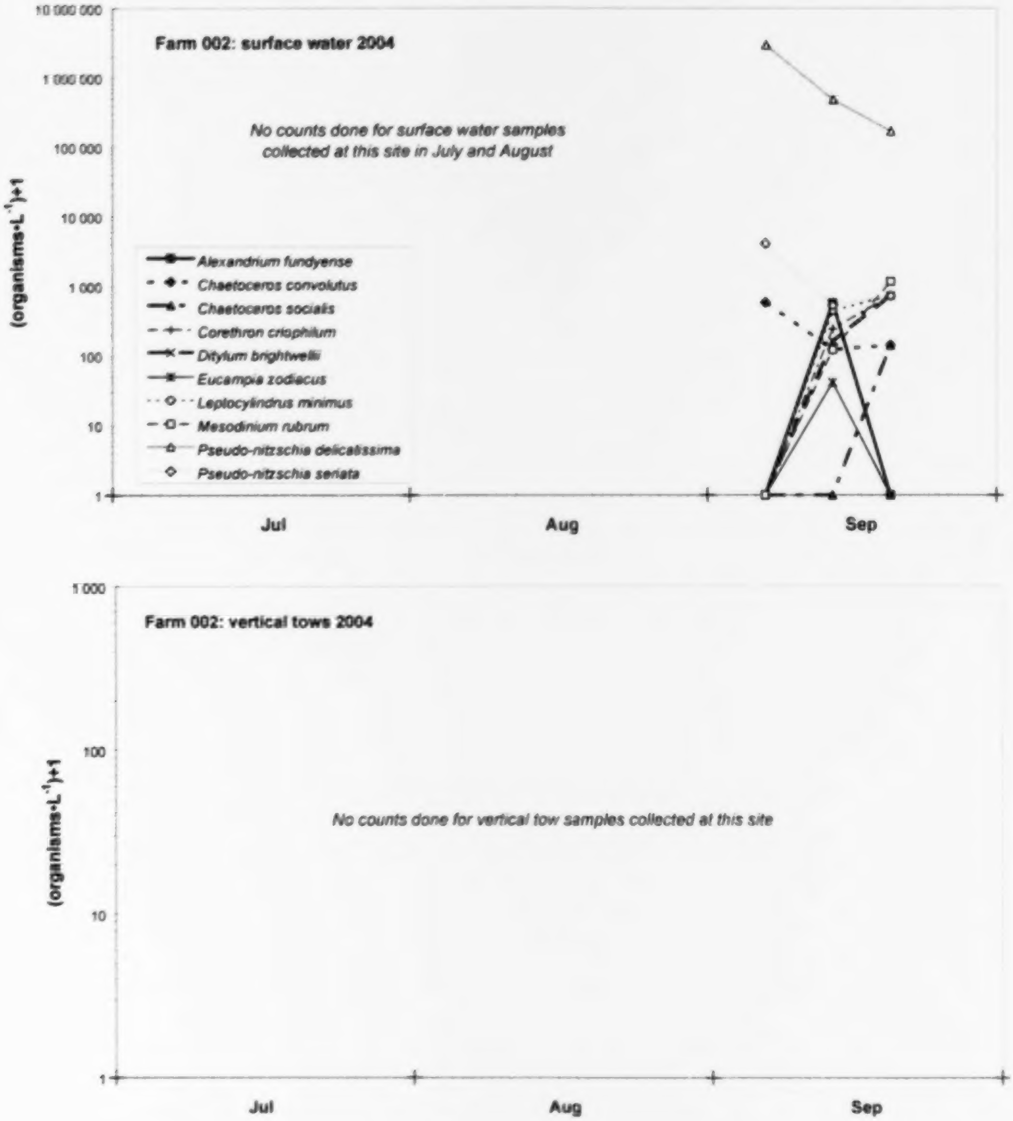
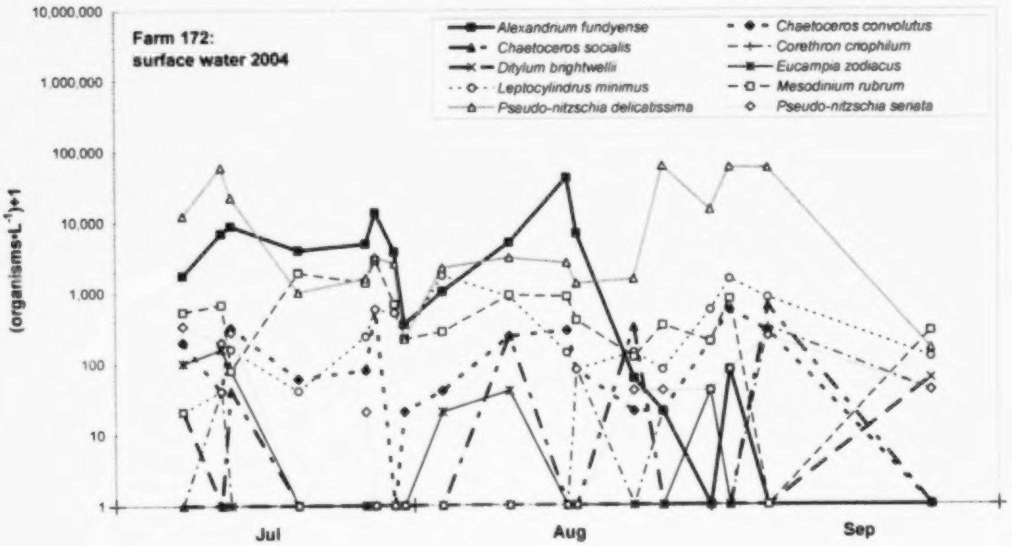


Fig. 6. Phytoplankton abundance in water samples collected at the four enhanced monitoring sites in 2004. Data shown are counts by DFO staff of samples collected by farm staff. Top: surface water samples. Bottom: vertical tow samples (values are averages over the depth of the vertical tow, 0-11 m).



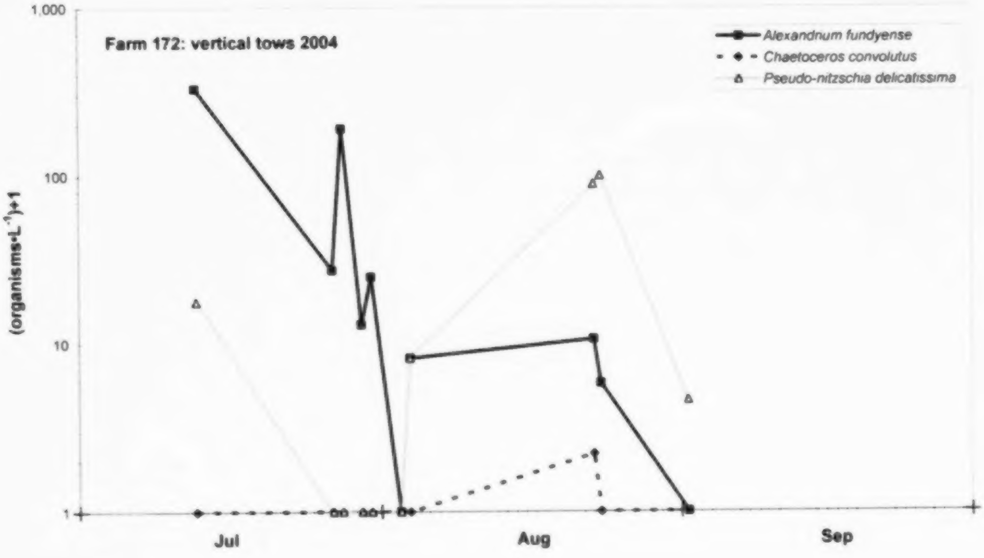


Fig. 6 continued.

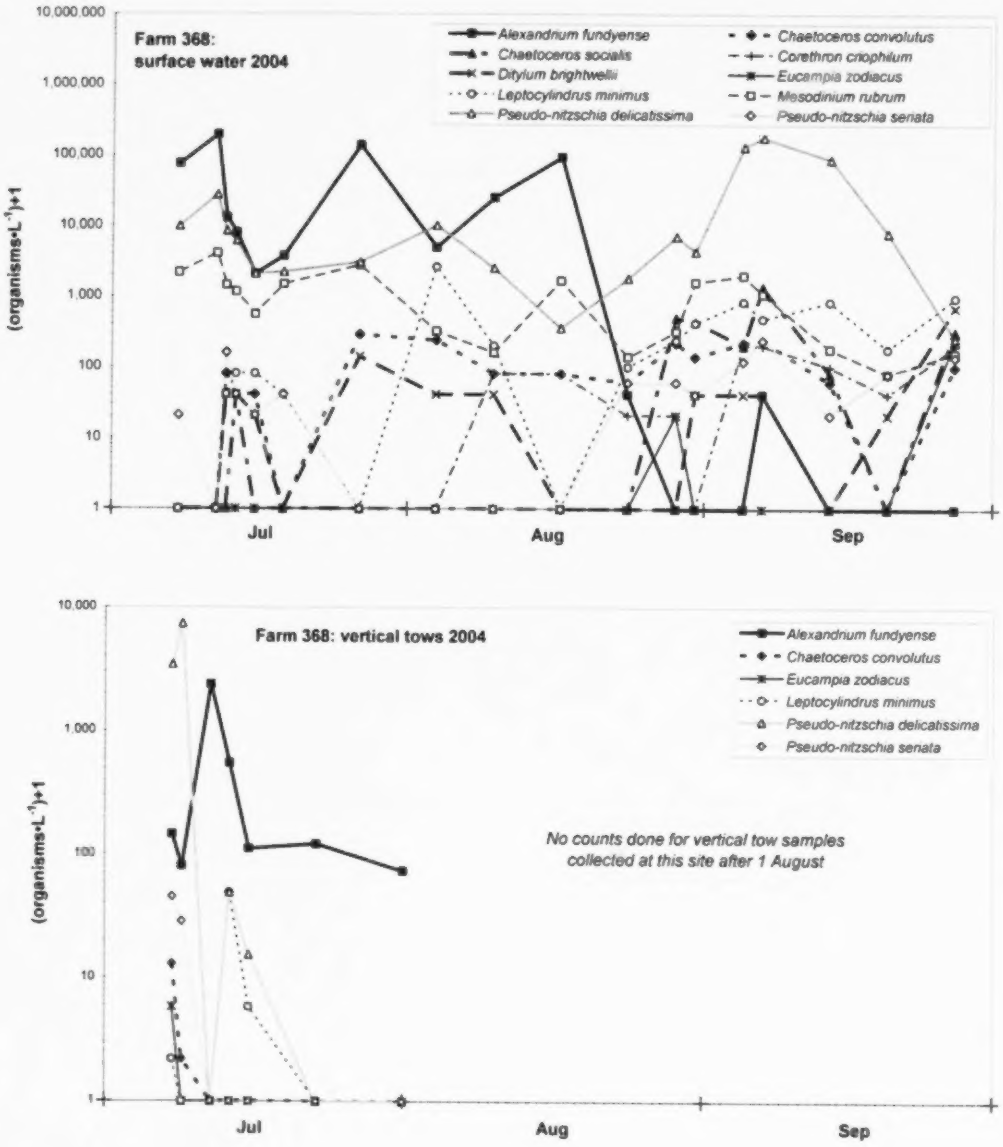


Fig. 6 continued.

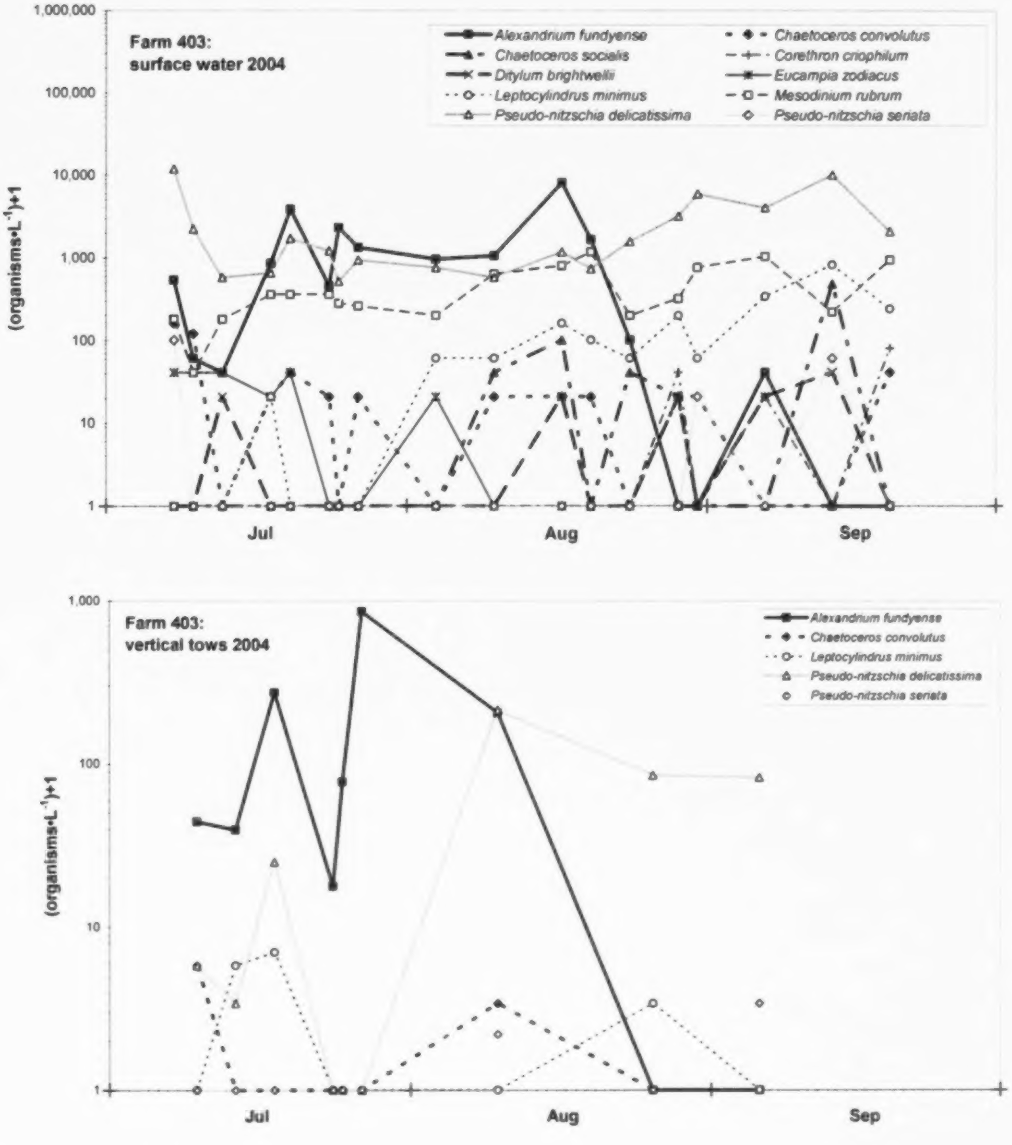


Fig. 6 concluded.

Appendix 3
Enhanced phytoplankton monitoring

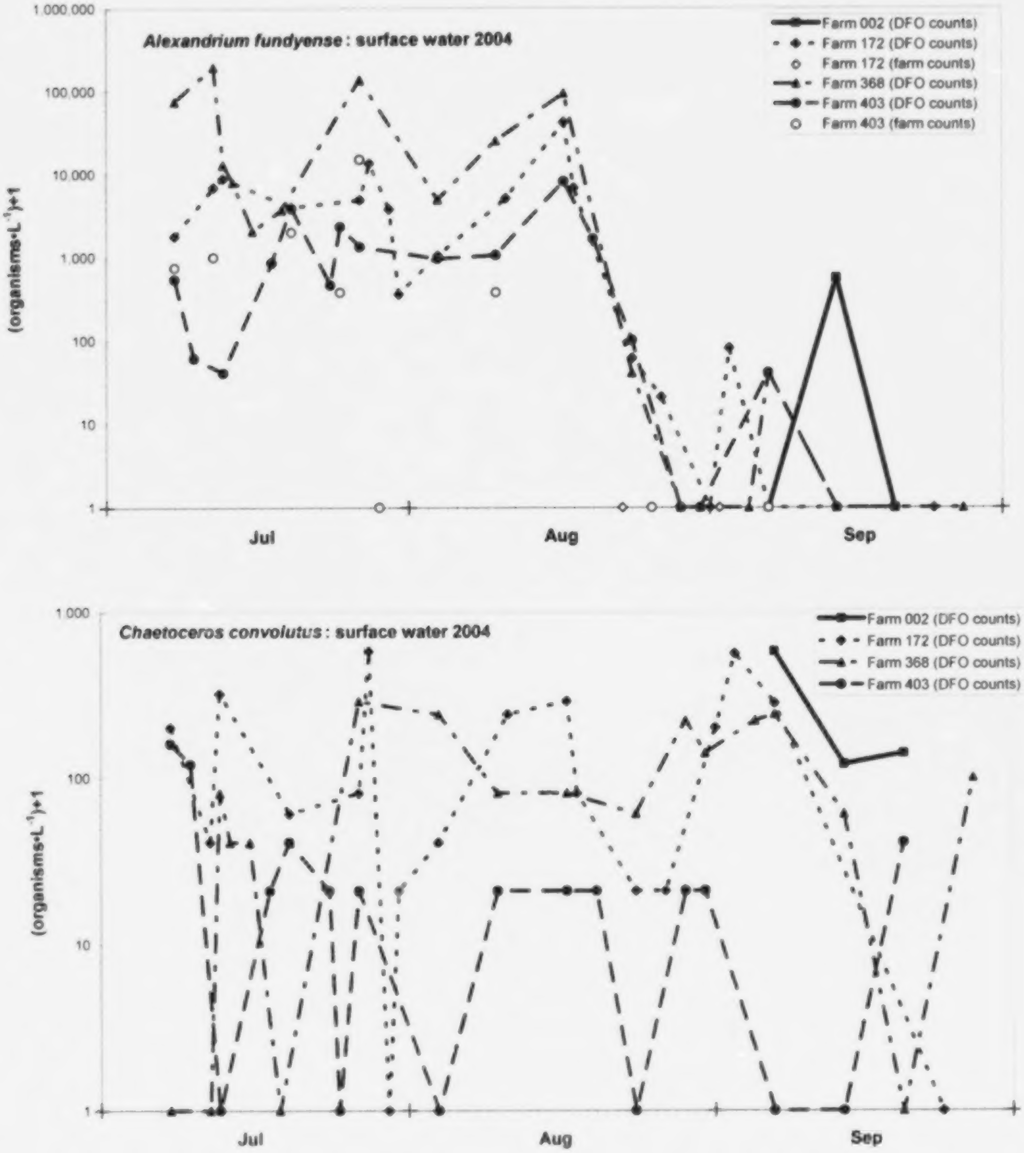
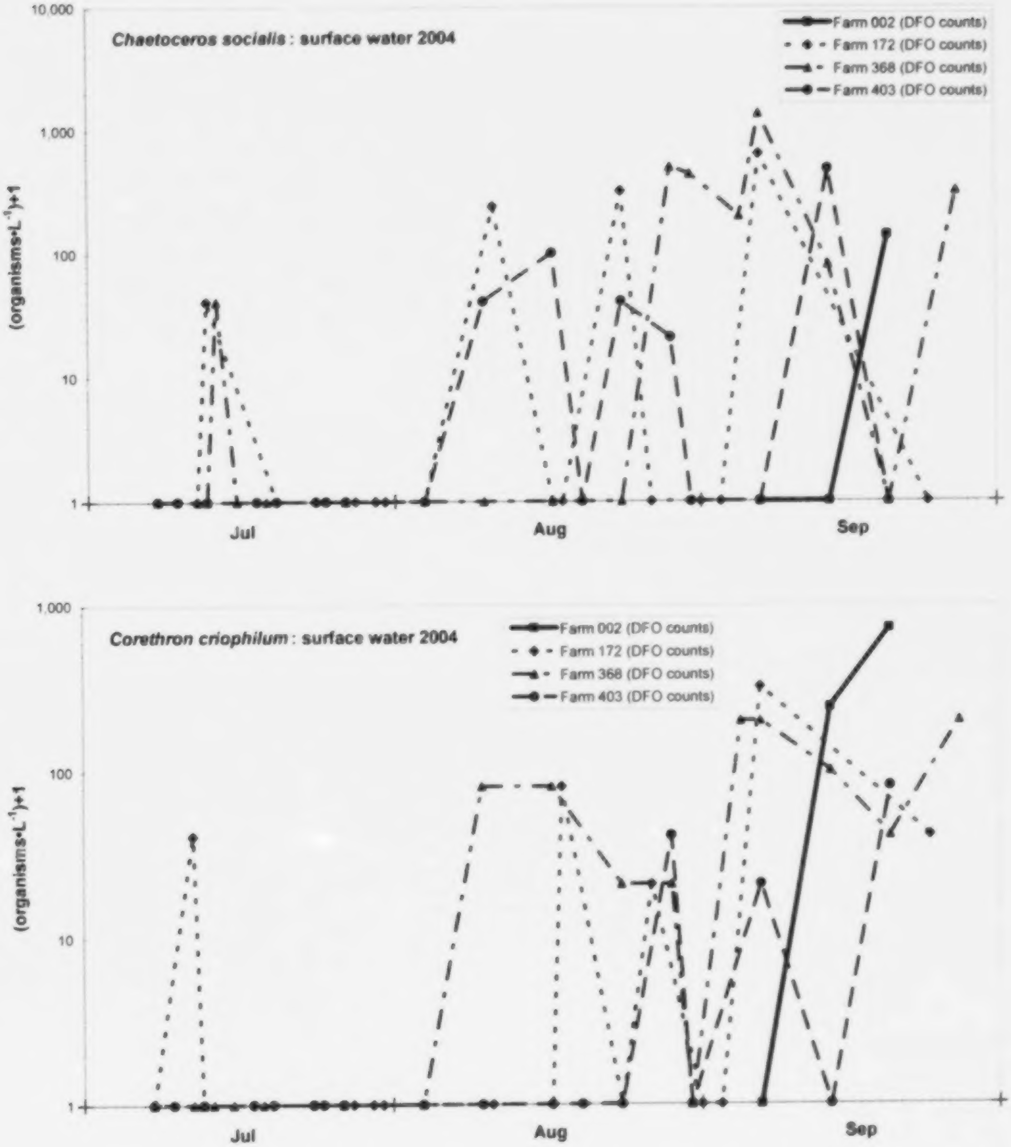


Fig. 7. Abundance of the most common phytoplankton species in surface water samples collected at the four enhanced monitoring sites in 2004. Data shown are counts by DFO and farm staff of samples collected by farm staff. Farm staff counts were only done for *Alexandrium fundyense*.



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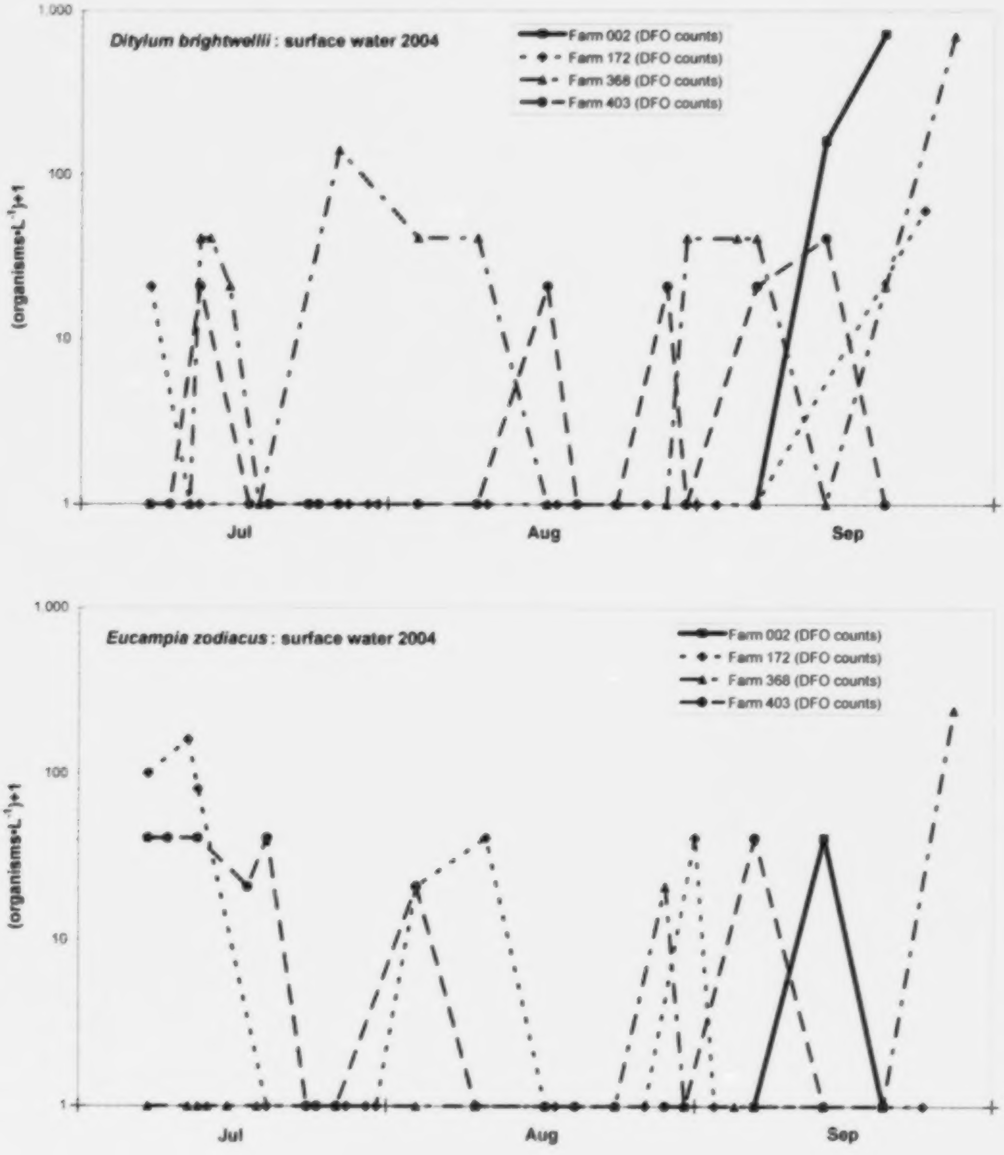

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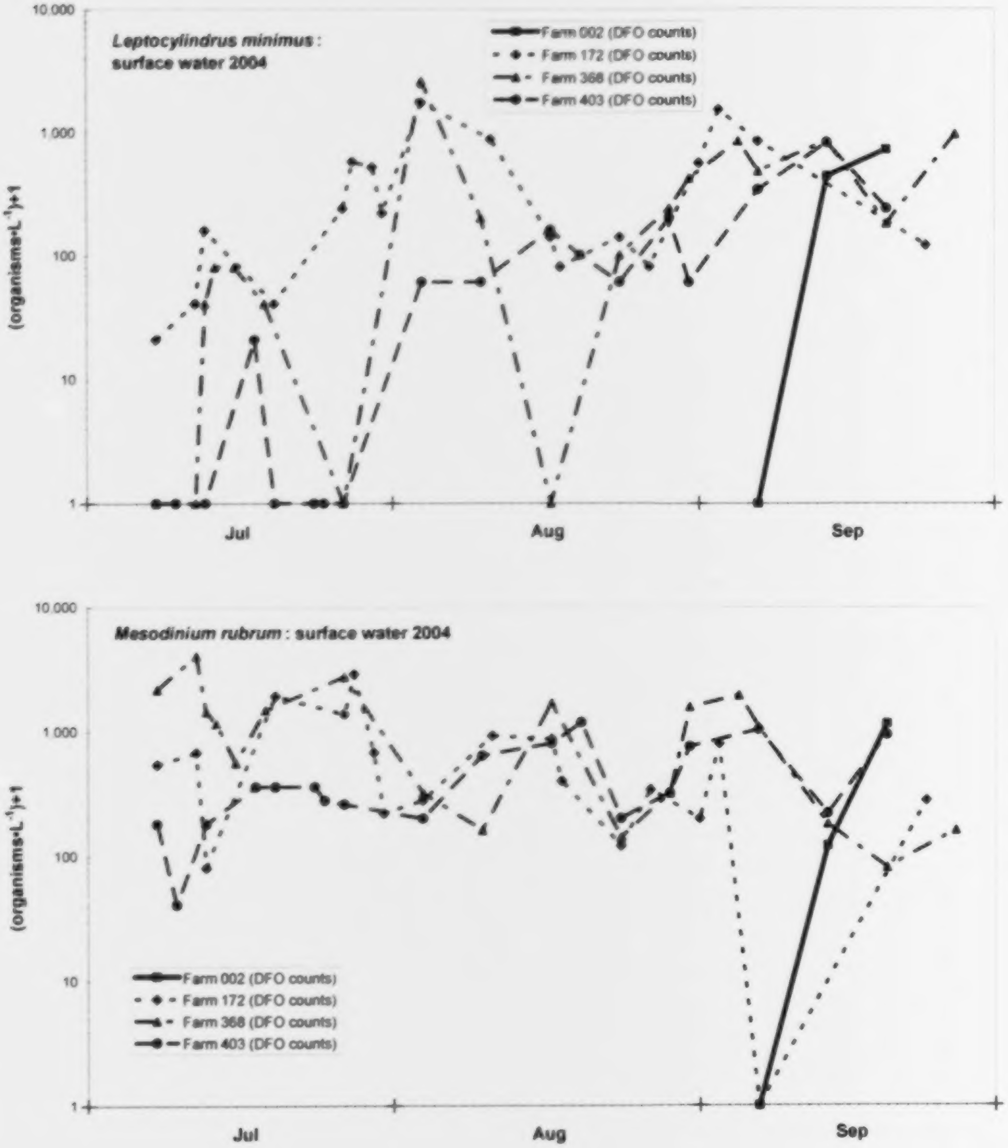

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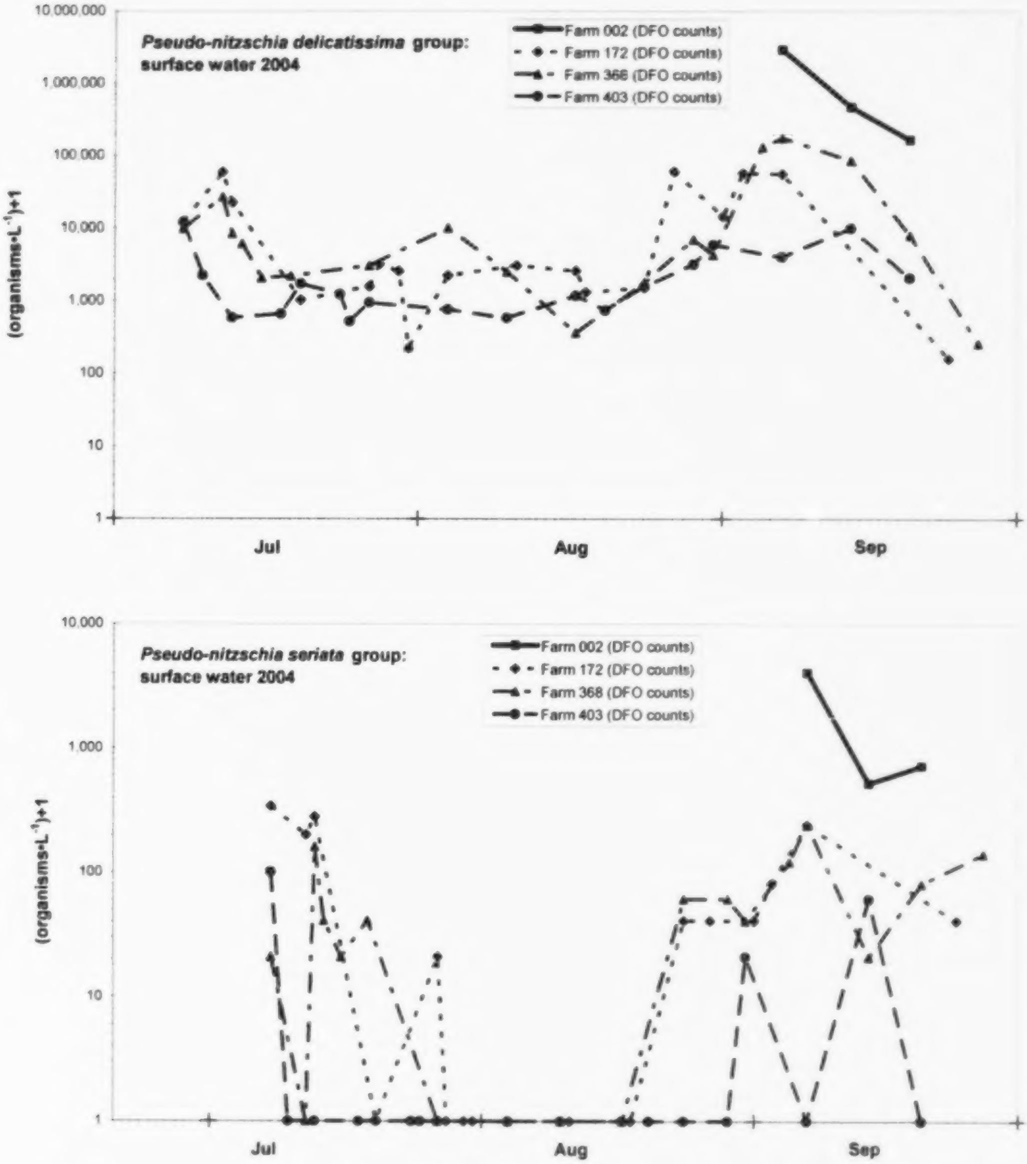


Fig. 7 concluded.

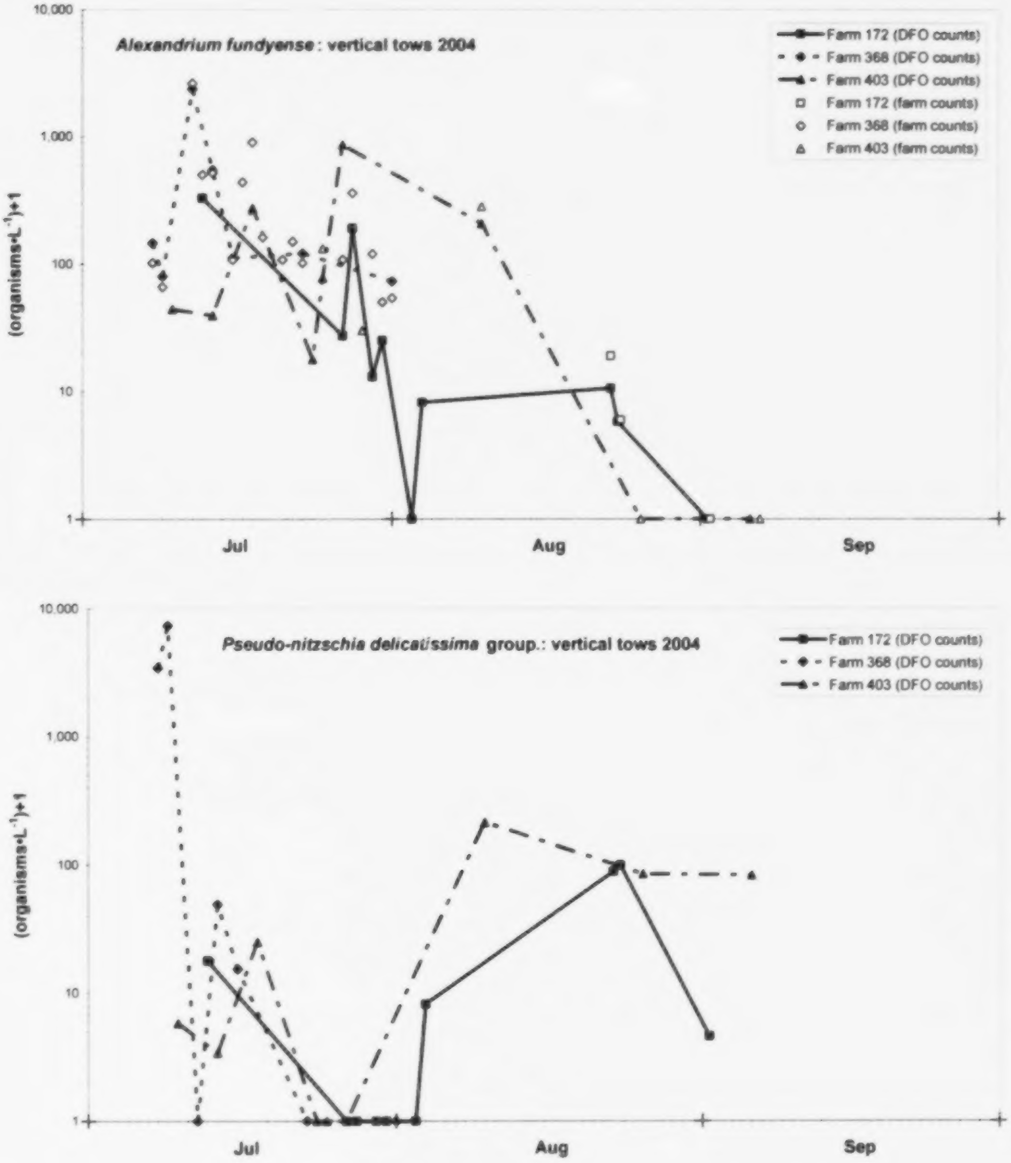


Fig. 8. Abundance of the most common phytoplankton species in vertical tow samples collected at the four enhanced monitoring sites in 2004. Data shown are counts by DFO and farm staff of samples collected by farm staff. DFO counts were not done for samples collected after the first week in August. Farm staff counts were only done for *Alexandrium fundyense.* Values are averages over the depth of the vertical tow (0-11 m).

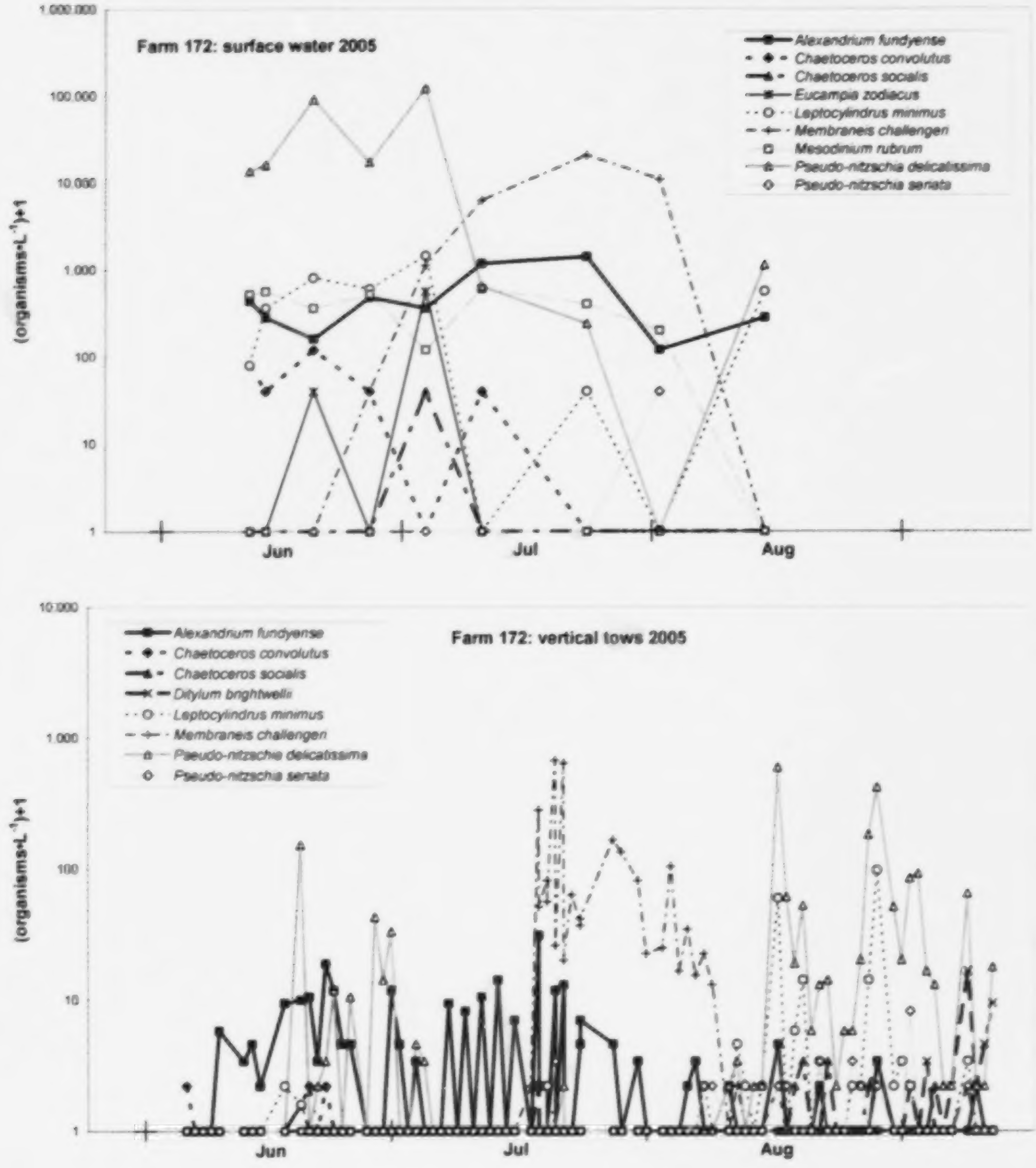
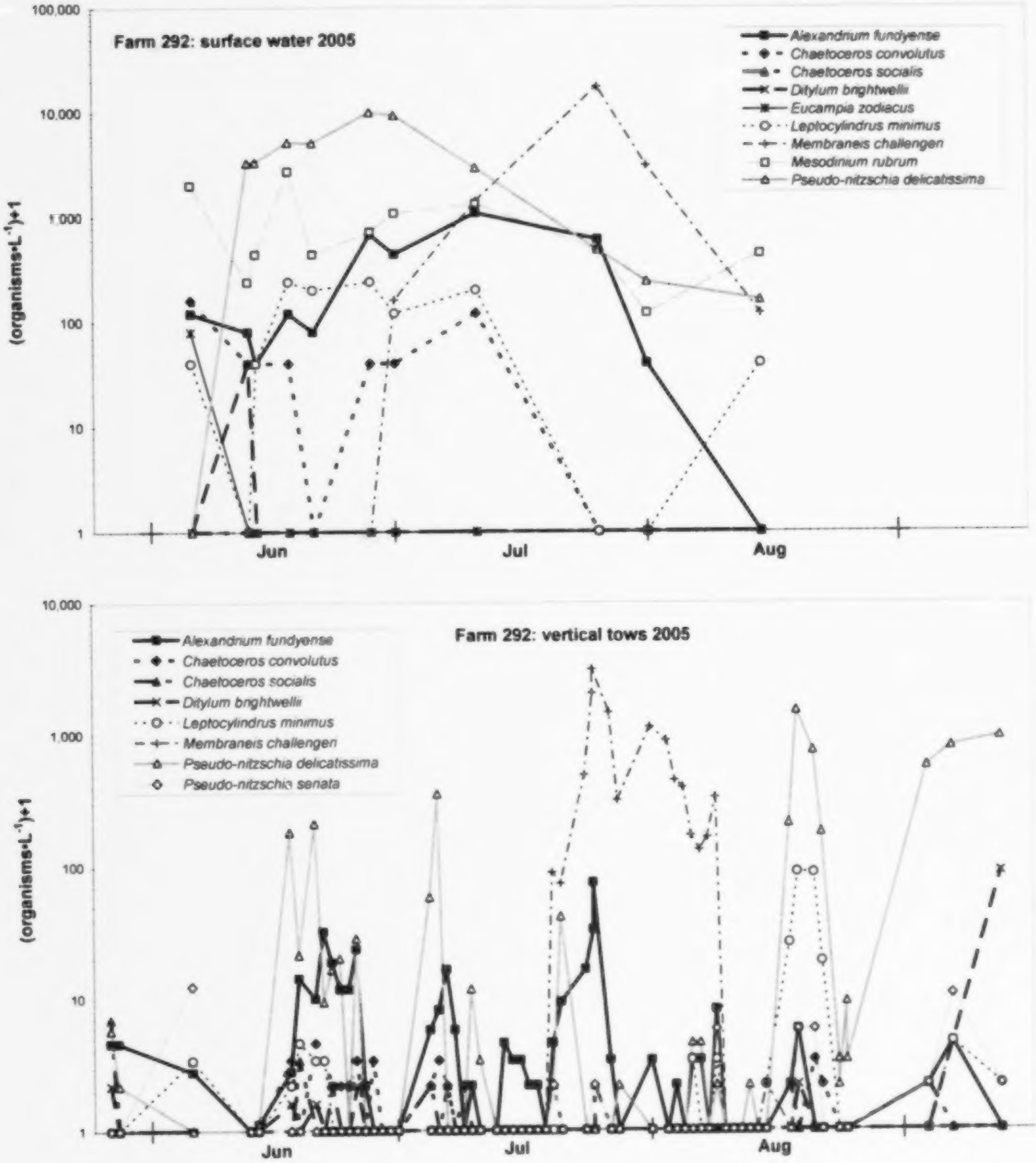


Fig. 9. Phytoplankton abundance in water samples collected at the four enhanced monitoring sites in 2005. Data shown are counts by DFO staff of samples collected by farm staff. Top: surface water samples. Bottom: vertical tow samples (values are averages over the depth of the vertical tow, 0-11 m).



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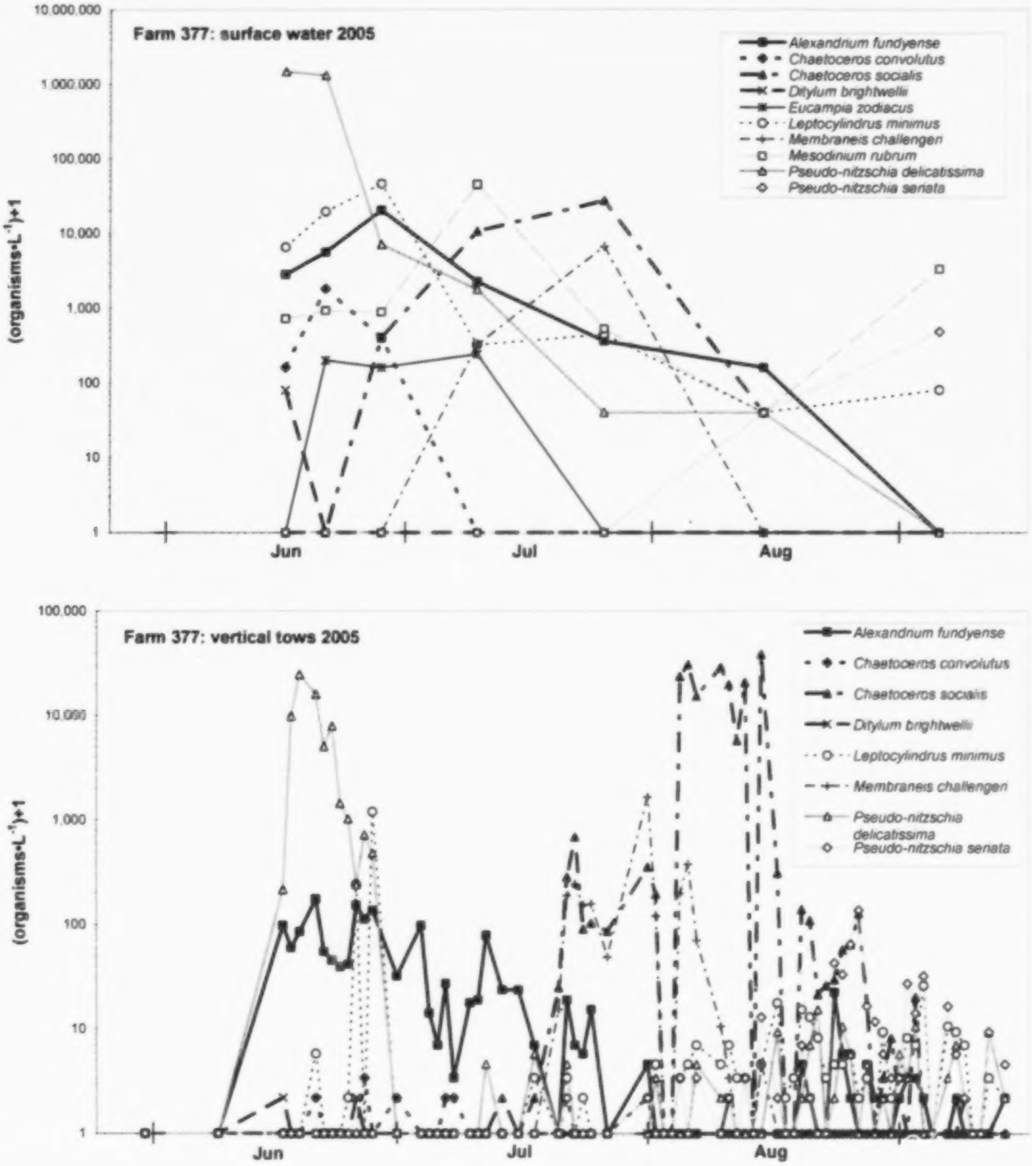

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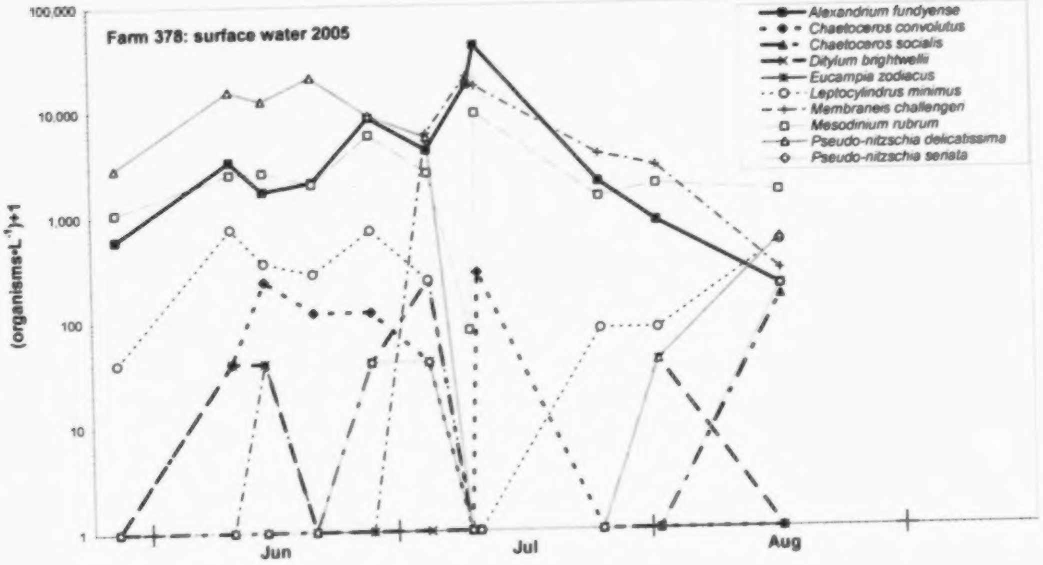


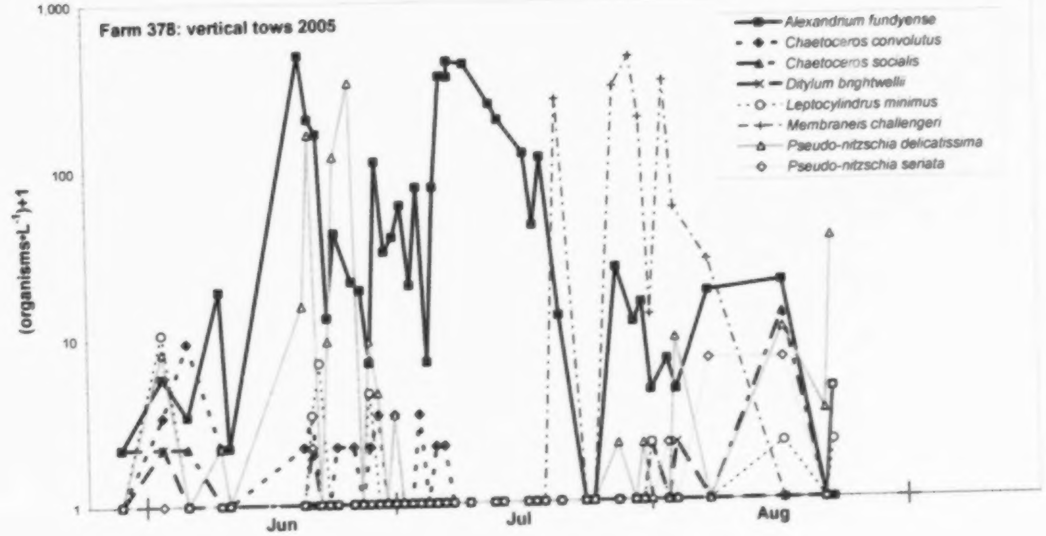


Fig. 9 concluded.

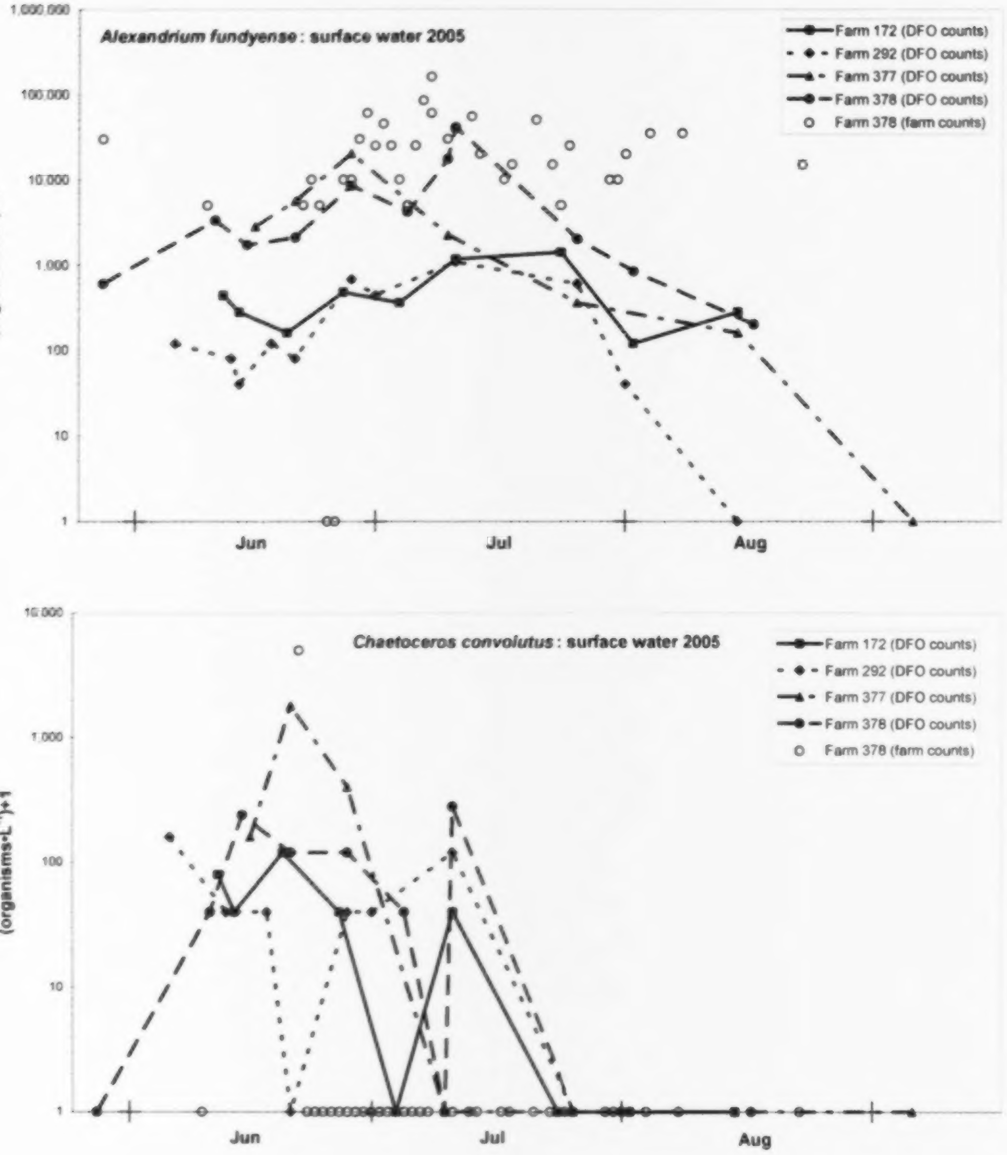
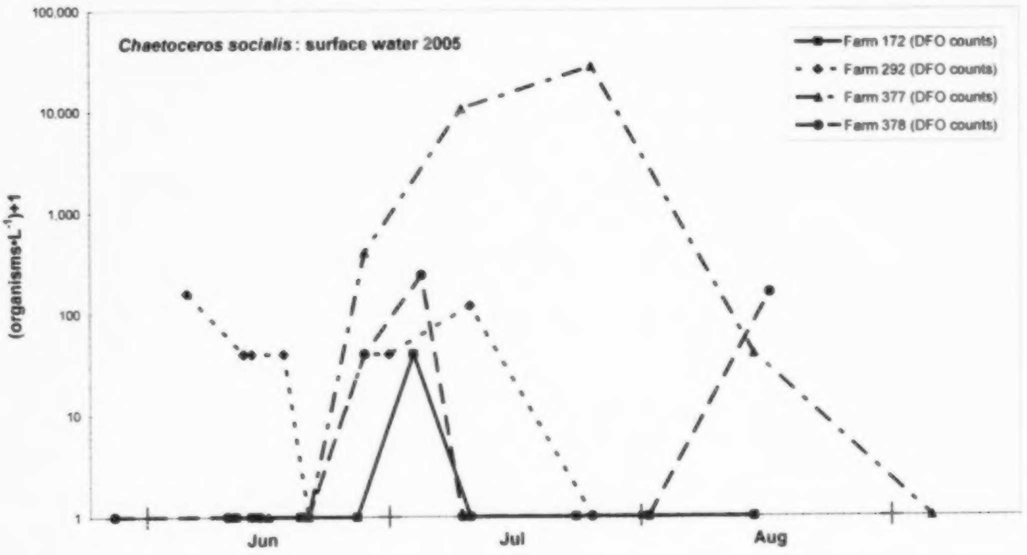
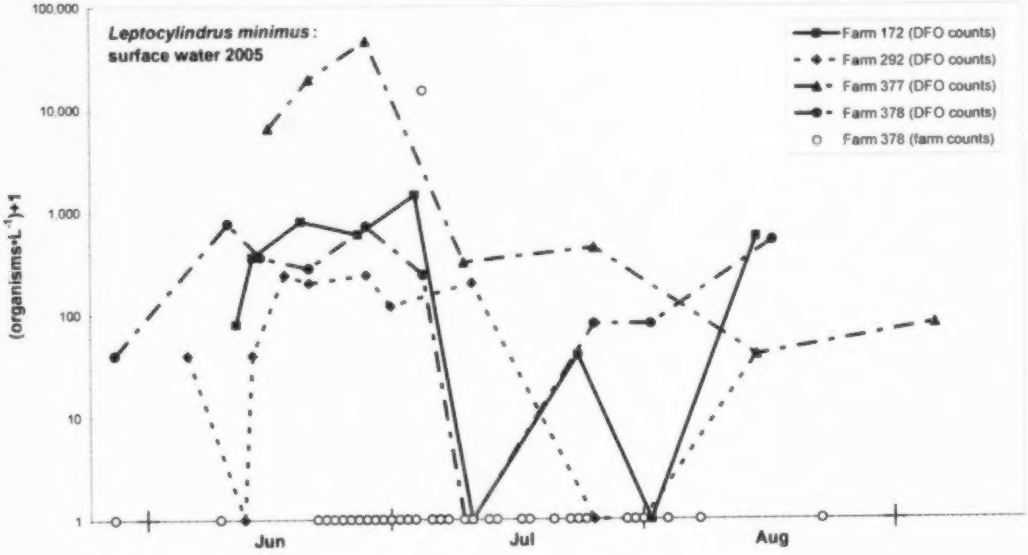


Fig. 10. Abundance of the most common phytoplankton species in surface water samples collected at the four enhanced monitoring sites in 2005. Data shown are counts by DFO and farm staff (where available) of samples collected by farm staff.





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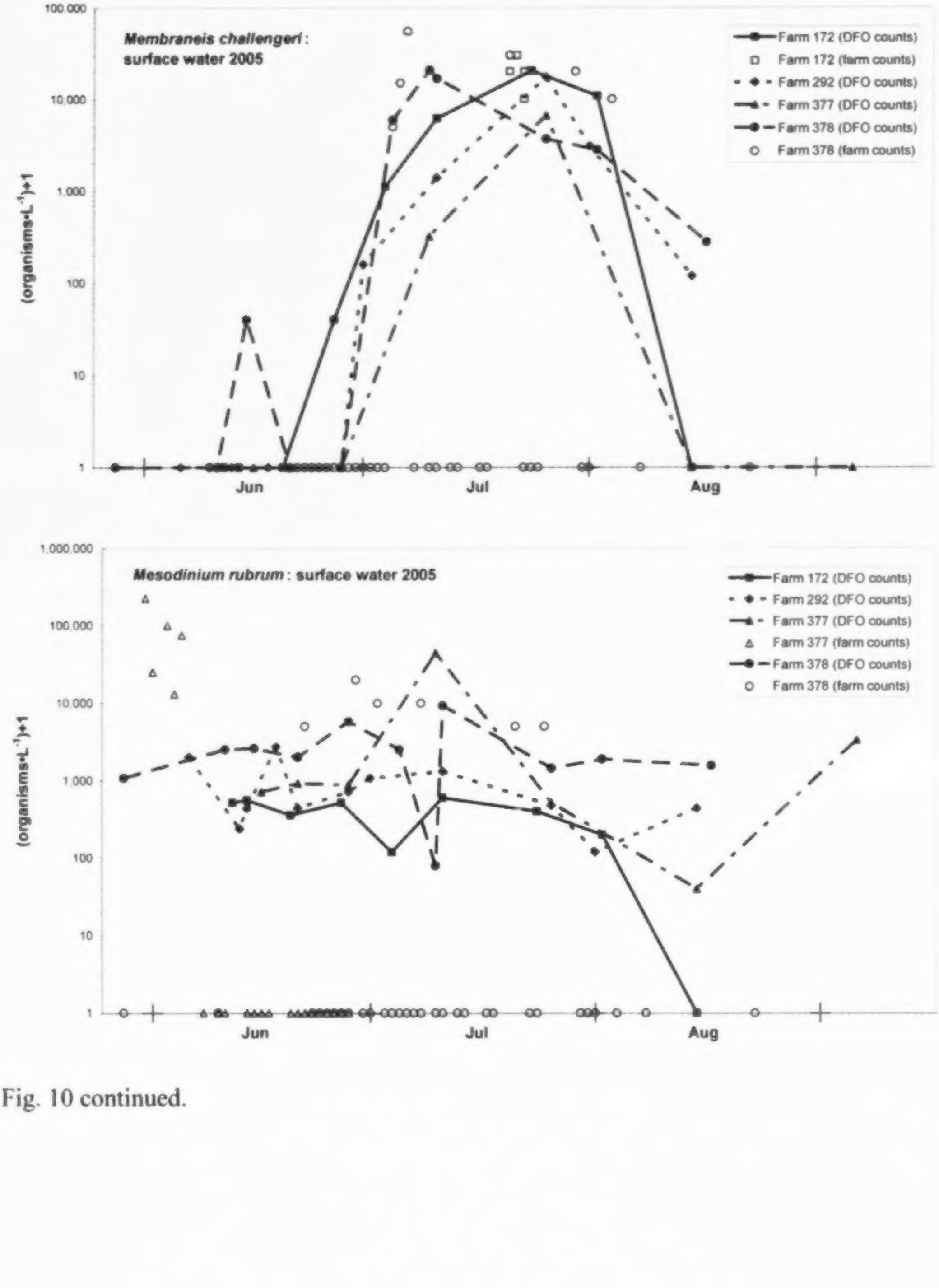

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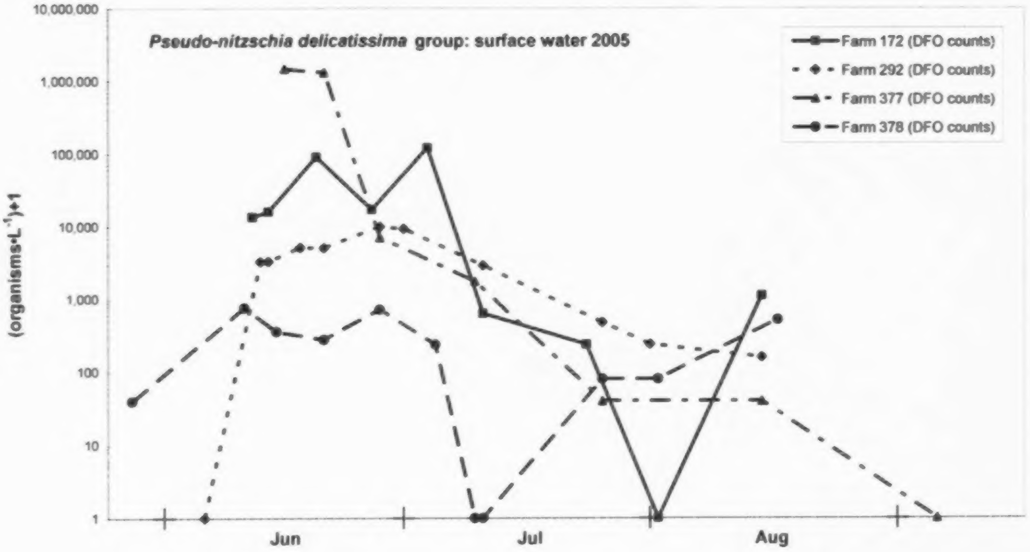

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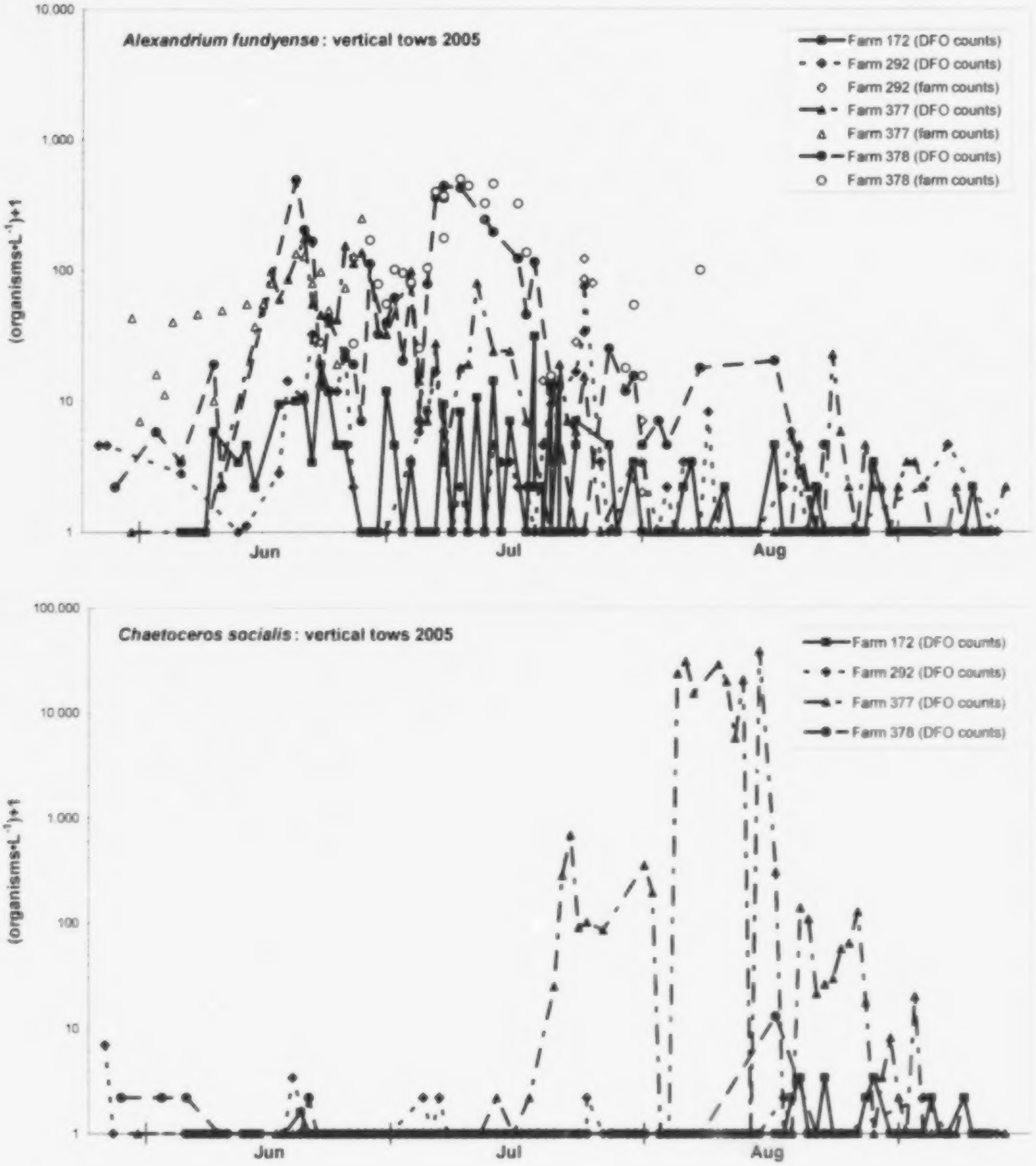
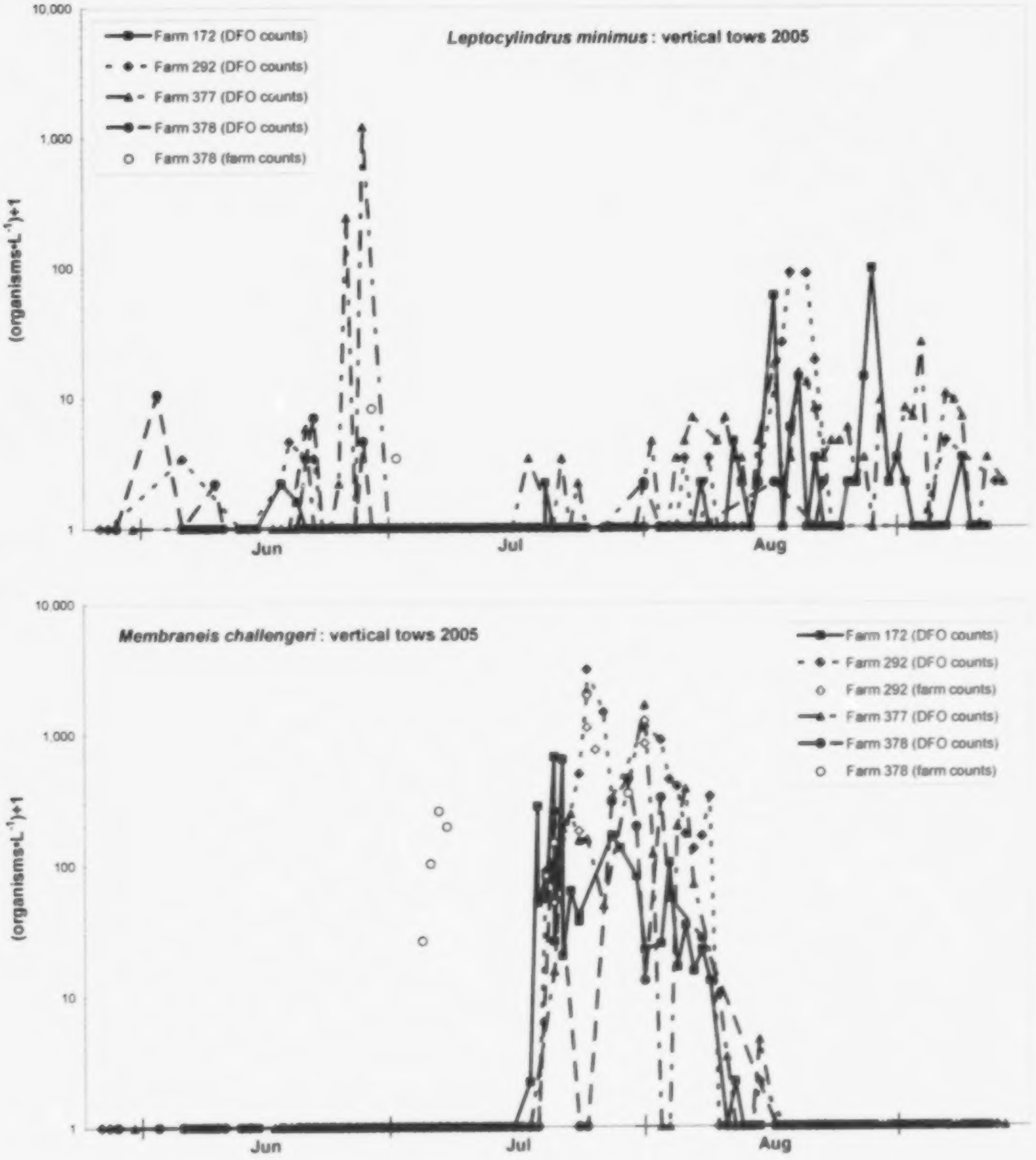


Fig. 11. Abundance of the most common phytoplankton species in vertical tow samples collected at the four enhanced monitoring sites in 2005. Data shown are counts by DFO and farm staff (where available) of samples collected by farm staff. Values are averages over the depth of the vertical tow (0-11 m).



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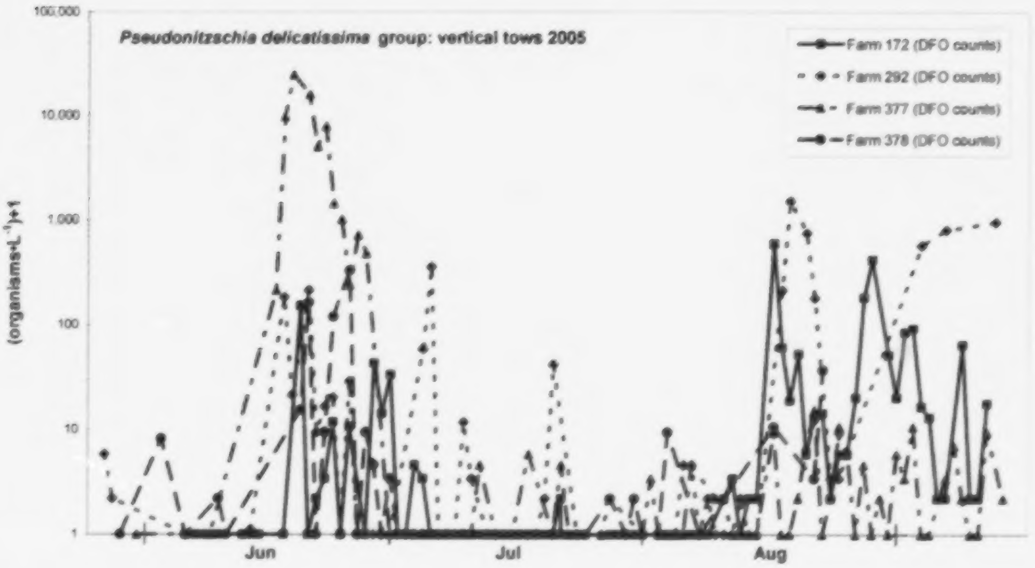

Fig. 11 concluded.

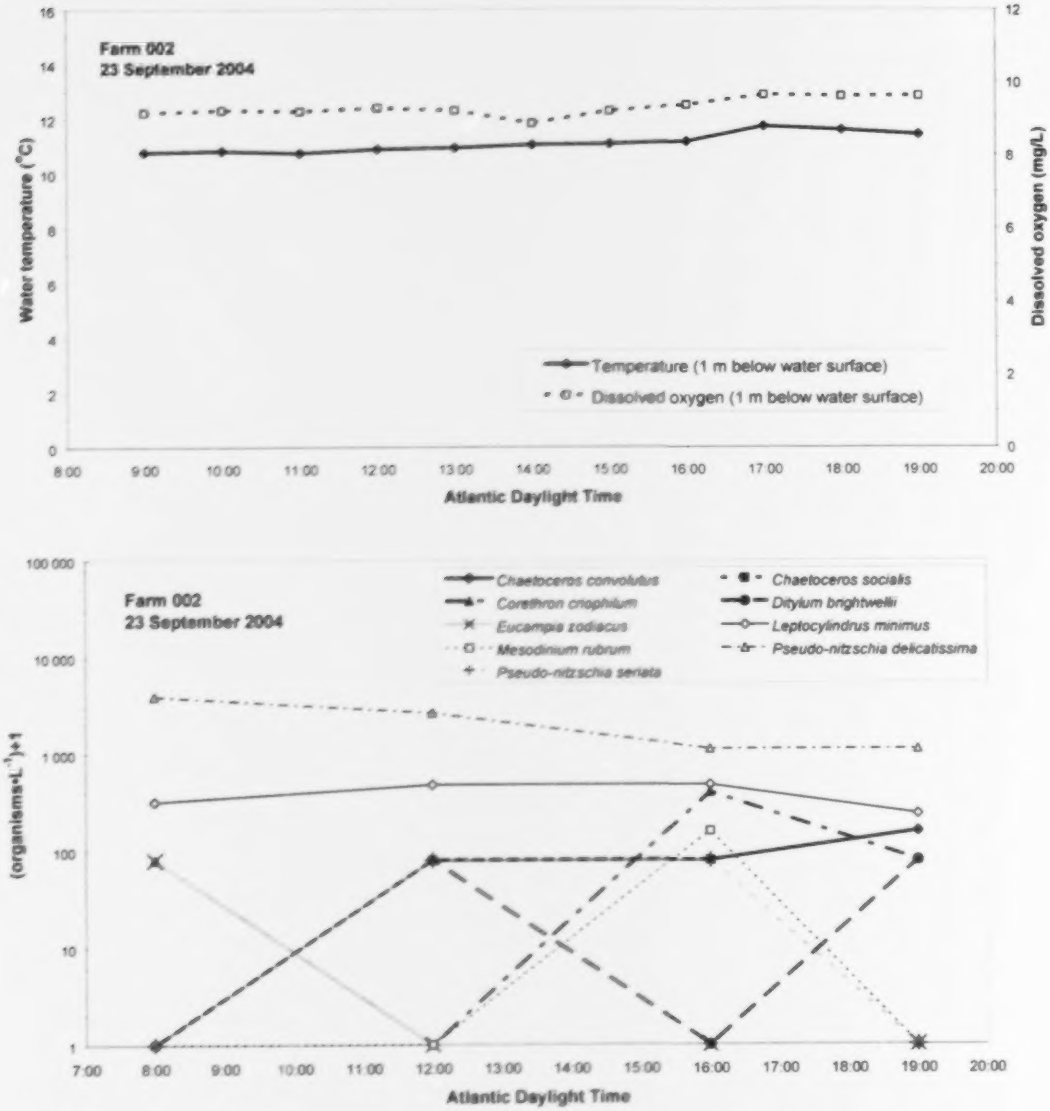

Fig. 12. Hourly data collected in surface water at farm 002 from 08:00 to 19:00 Atlantic Daylight Time on 23 September 2004. Top: water temperature and dissolved oxygen levels (1 m below surface). Bottom: abundance of phytoplankton species.

PATTERNS OF ABUNDANCE FOR ELEVEN SPECIES OF HARMFUL ALGAE FOUND TO OCCUR IN SOUTHWESTERN NEW BRUNSWICK BETWEEN 1987 AND 2004

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Description of Study

The appearance of harmful algal species in and around where shellfish and fish are grown or harvested is problematic with often devastating effects. A retrospective summary of the abundance of harmful algal species in the vicinity of aquaculture operations can provide insight into the spatial and temporal tendencies of these species. Phytoplankton abundance data is available from weekly to monthly sampling which has been conducted throughout the year at four sites in the SWNB area of the Bay of Fundy (Fig. 1) since 1987 (Wildish et al. 1988, 1990; Martin et al. 1995, 1999, 2001, 2006). This report analyzes phytoplankton abundance data for the period 1987-2004.

The first visualization of the count data targets the "bloom scenario." With blooms, the concern is with an acute effect on fish and shellfish. We are looking for an episode of extremely high cell density and are interested in the seasonal timing of the episode. "Extremely high" is difficult to define in a generic sense. Species differ in size, thereby affecting the number which can be contained in a given volume. Likewise, the degree of harm each species is capable of is not standard for similar cell densities. Physical environmental differences across locations introduce variation in the carrying capacity for each species and possibly their harmful effects. Thus, the identification of blooms must be a species-specific exercise that requires a reasonably long time series of observations collected at a number of widespread locations in the domain of interest. One method for describing a bloom is to single out the maximum cell density in each year, at each location, and plot these as a time series (Fig. 2). To make these maxima less a function of chance, the time base of the statistic is spread to cover a month's worth of samples. Averaging these samples controls for variation in the number of samples per month. The time series constructed in this way are shown in Fig. 2. Eleven species and four locations are represented using samples of surface water. These plots reveal the synchronicity among sites and species. They show a frequency of occurrence over the time series and show the variation in timing within a year. When examining these plots, it is important to consider the degree to which we can infer specific preferences for a location, and the extent to which we can infer an origin for a bloom or favorite environmental conditions.

Results by Species

Plots showing the month of maximum mean monthly cell counts and the maximum mean monthly cell counts at each monitoring site for each species analyzed are presented in Fig. 2. Summary results for each species analyzed are presented below. More detailed results for *Alexandrium fundyense* can be found in Page et al. (2005, 2006), for *Eucampia zodiacus* in

Martin et al. (2007a), and for *Mesodinium rubrum* in Martin et al. (2007b). Reports on other species are in preparation.

Alexandrium fundyense

At its peak this species averaged more than 100 000 cells·L^{-1}. This occurred once at the offshore site 16 in August. The cell density signal was strongest at this site, with all the significant episodes (years 1989, 1993, 2001, 2003 and 2004) mirrored with fading magnitude at sites 15 and 3. Site 17 showed virtually no signal. A pattern such as this is suggestive of a trend in the distribution of cells from offshore to inshore, with an origin at site 16. It also suggests that the physical environment favors the growth of *A. fundyense* at site 16. There is, however, no evidence from the timing of the blooms that this should be the case, since the relative order of months with the maximum mean cell count did not have any consistent order. July was the most common month for a bloom, and sites 3, 15 and 16 showed the most synchrony in the timing.

Chaetoceros convolutus

This species was not present every year. It appeared to bloom in June most often, a full month before *A. fundyense*. Thus, a peak occurrence in 1989 at all sites except 17 was not coincident with the *A. fundyense* peak. In any case, the cell density, even at its peak, was below 1000 cells·L^{-1}. Unless these cells were big, there would be no reason to believe both blooms could not occur simultaneously. The cell density signal was similar for sites 16, 15 and 3, with virtually no signal at site 17.

Chaetoceros socialis

Later with its blooms than either *A. fundyense* or *C. convolutus,* it averaged over 100 000 cells·L^{-1} on two occasions, once at site 17 in 1999 and at site 3 in 2003. The later bloom time means it was not coincident with the previous two species, even when they bloomed in the same year (e.g. 2003). All sites shared the same major features in the bloom time series where all the activity has occurred in the last 6 yr, except at site 15 where a bloom was also observed in 1990. The more inshore sites (3 and 17) showed a slightly stronger signal than the more offshore sites (16 and 15).

Corethron criophilum

This species mainly bloomed in October and had only one notable episode in the 18 yr of the series, when the cell density peaked at 3000 cells·L^{-1} in 1990. This bloom was observed at all sites except 17. A minor peak of less than 1000 cells·L^{-1} was observed at all sites in 2002. The bloom in 1990 did not conflict with any of the other species reviewed thus far, due to its lateness.

Ditylum brightwellii

This species was a consistently late bloomer (October) that had one major episode in 2003. This bloom was observed at all sites except 17, with site 16 having more than 80 000 cells·L^{-1}. A gradient of cell density was apparent between site 17, which had a paucity of cells and was located well inshore, and the other three sites. The average cell density oscillated below 20 000 cells·L^{-1} at sites 3, 16 and 15, with the exception of 2003 mentioned above.

Eucampia zodiacus

This species was not detected in every year. Blooms in the later half of the series occurred in October, in contrast with June or July maxima in the first half of the series. The major blooms occurred in the latter half of the time series, notably in 1999 and 2002. While each site exhibited the same episodes, there was a clear dominance at site 17, where numbers peaked above 80 000 cells·L^{-1} in 2002, and a scarcity at more offshore sites like 15 and 16. This peak did not conflict with the *C. socialis* peak of 2002, as it was earlier. Site 17 differed from the other sites in that a peak in cell density in 1999 was followed by an even larger one in 2000.

Leptocylindrus minimus

This is another example of a species with greater numbers inshore (site 17). The major peak of 1990 was represented at the other sites to a lesser degree, and the minor peaks of 1994, 1997, 2002, and 2004 were barely visible at all. More than 100 000 cells·L^{-1} was observed at site 17 in July 1990. The month of peak abundance tended to vary for all sites. The 1990 bloom by *C. criophilum* occurred later in the year.

Mesodinium rubrum

The inshore signal at site 17, which had a mean cell density of more than 100 000 cells·L^{-1} in August 1989, dominated the other time series. A second peak of 40,000 cells·L^{-1} occurred in August 2001. Activity at other sites and in other years occurred below a level of 20,000 cells·L^{-1} and was not a faithful reflection of the cell density at site 17. While most peaks occurred in August, there was variability associated with the timing from year to year and site to site. The peak at site 17 in 1989 was not coincident with peaks of other species (*A. fundyense*, *C. convolutus*) in the same year, because they did not occur at site 17.

Pseudo-nitzschia delicatissima group

This species had by far the greatest cell densities reported for any species. More dominant in the offshore sites (16 and 15), its major blooms occurred in 1995, with 500 000 cells·L^{-1}, and 1988, with 300 000 cells·L^{-1}. Site 15 had most of the same events as site 16, while the more inshore sites (3 and 17) exhibited some of them at more moderate levels. These peaks were mainly in August.

Pseudo-nitzschia seriata group

This species had the second greatest cell densities reported for any harmful algal species. Densities below 50 000 cells·L^{-1} were not visibly different from zero counts. Sites 15 and 16 showed single peaks in 2002, with densities of more than 250 000 and 214 000 cells·L^{-1}, respectively, occurring in September. Site 3 showed a much smaller peak, with just under 100 000 cells·L^{-1} in September, while site 17 had no peaks. Most blooms appeared in September.

This was the only example where two species (*P. seriata* group and *Pseudo-nitzschia* sp.) reached bloom proportions in the same year, month, and location. Since these densities represented an average for the whole month, it is possible that it did not exactly overlap with the 2002 bloom of *Pseudo-nitzschia* sp.

Pseudo-nitzschia sp.

This species bloomed late in the year, September–October, when it appeared. It was largely absent, except for a bloom of more than 50 000 cells·L^{-1} in September 2002 at site 15, and was not coincident with any of the other species, except for the *P. seriata* group. It was found at inshore sites at very low levels.

General Results and Discussion

A general feature of all of these time-series plots (Fig. 2) is that the different harmful algal species do not share identical temporal and spatial windows in which they become dominant. Major blooms by a species occur relatively infrequently but are seen to varying degrees at all the sites. A species rarely dominates in inshore and offshore locations, showing a preference for one type over the other. Lastly, there does not appear to be any clustering of the blooms of all species in any part of the temporal domain (annually or monthly), but depending on the offending species, certain locations may be safe and others impacted.

In Fig. 3, 4 and 5, one can see the distribution of blooms by site and either month or year for each species. A bloom is defined for each species as the top 5% of mean monthly cell counts observed in the domain over the 18-yr time series after discarding zero counts. The application of this rule did a good job of capturing the major events occurring in the domain, as observed in the time series, and determined that there were 48 significant events. When interpreting these plots, notice that each year/site or month/site location on the plot could potentially contain a domino-like pictograph. This pictograph only occurs where and when there was a bloom by at least one of 11 harmful algal species. Each pictograph contains an array of 12 squares, with a specific square designated for each of the 11 species, plus one extra. Because the species each have a designated location in the array, in addition to when and where the blooms occurred, we also know which species was responsible.

In the site-year plot (Fig. 3), the occurrence of blooms seems largely restricted to the beginnings and ends of the time domain. Site 16 had 10 bloom years out of 18, with 14 bloom events in those 10 years. These blooms were caused by 10 of the 11 possible harmful algal species. Nearby, at site 15, with six bloom years out of 18, there were 15 bloom events by 10 of 11 species. Further inshore at site 3, there were seven bloom years, with 10 bloom events by eight species, while deep inside Passamaquoddy Bay at site 17, there were eight bloom years, with nine bloom events by five species. In years where there were three or more sites with a bloom, a single species can be seen to have occurred at each site, whereas years with two or fewer affected sites had no species in common. From 1999-2001 only sites 16 and 17 experienced six blooms by six different species, compared with 2002-2004 when all four sites experienced 22 blooms, frequently by the same species.

The site-month plots (Fig. 4 and 5) show that blooms occurred from June to November. At sites 3, 15 and 16, species bloomed in September, while site 17 had a more even distribution (among months of the year) of blooms.

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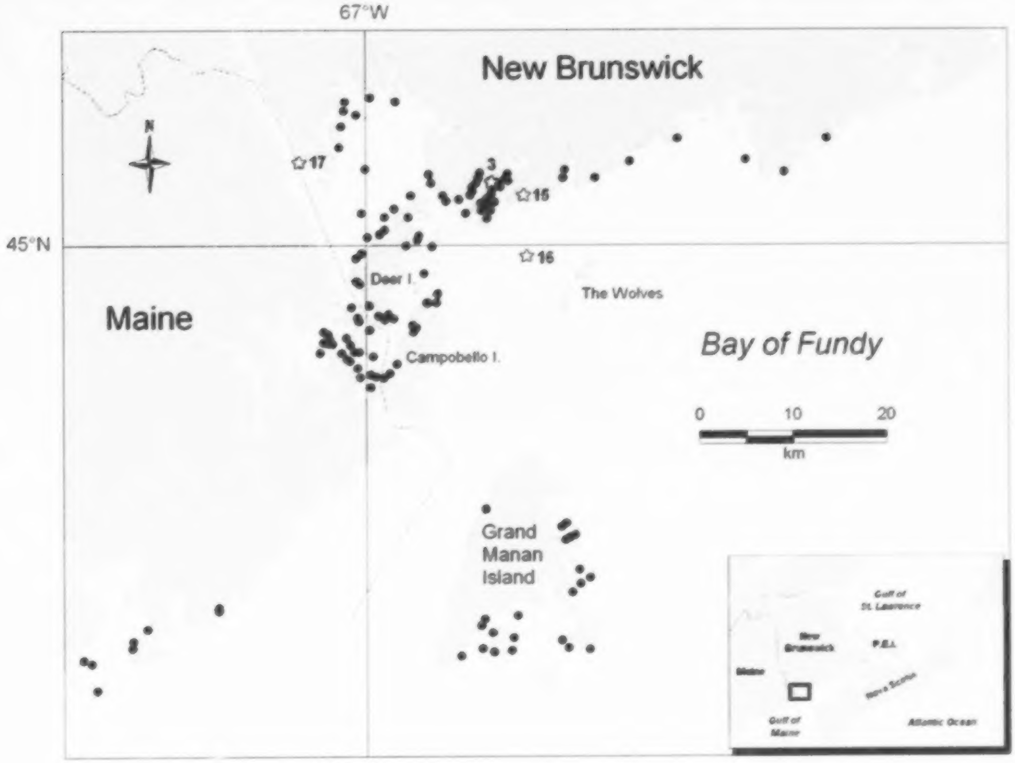

67°W
45°N
New Brunswick
N
17
3
15
16
Deer I.
The Wolves
Maine
Campobello I.
Bay of Fundy
0
10
20
km
Grand Manan Island
Gulf of St. Lawrence
New Brunswick
P.E.I.
Maine
Nova Scotia
Gulf of Maine
Atlantic Ocean

Fig. 1. Map of the SWNB area showing the four phytoplankton monitoring sites (star symbols) sampled since 1987: 17 = Brandy Cove; 3 = Lime Kiln Bay; 15 = Deadmans Harbour; 16 = the Wolves Islands. Black circles represent finfish farm sites in 2004.

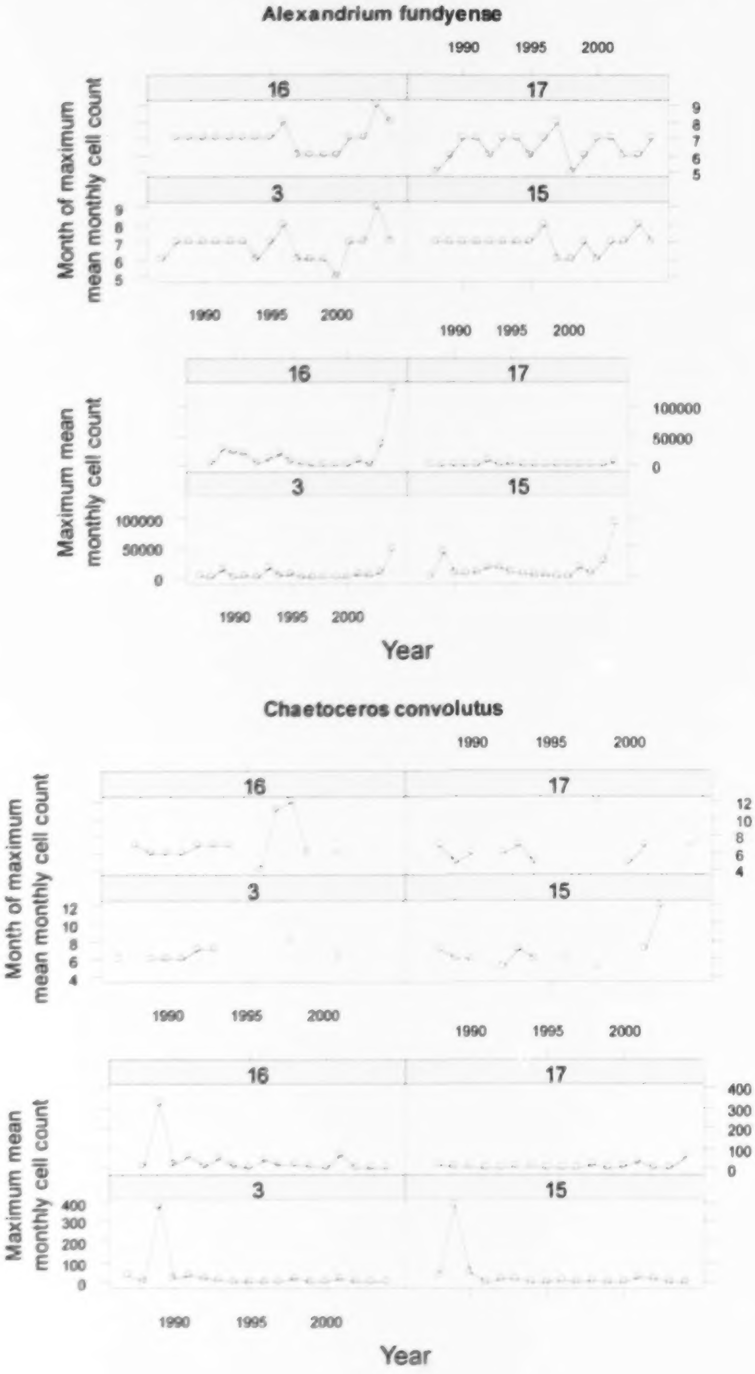
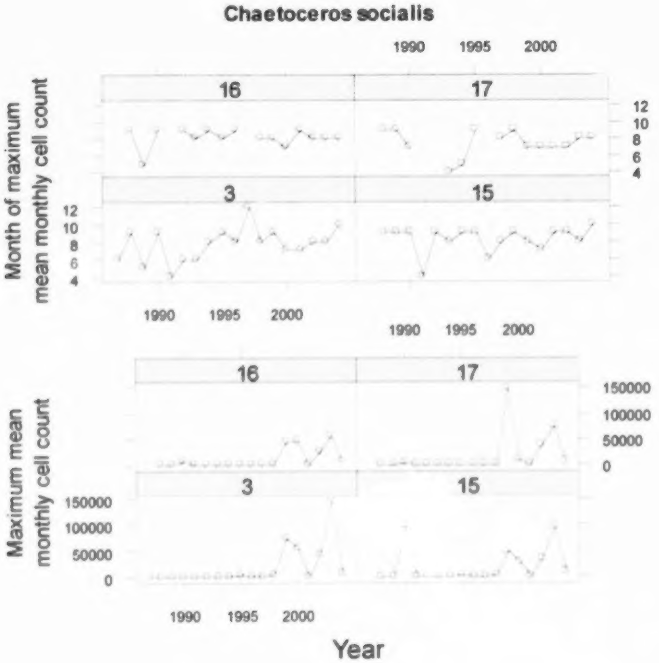
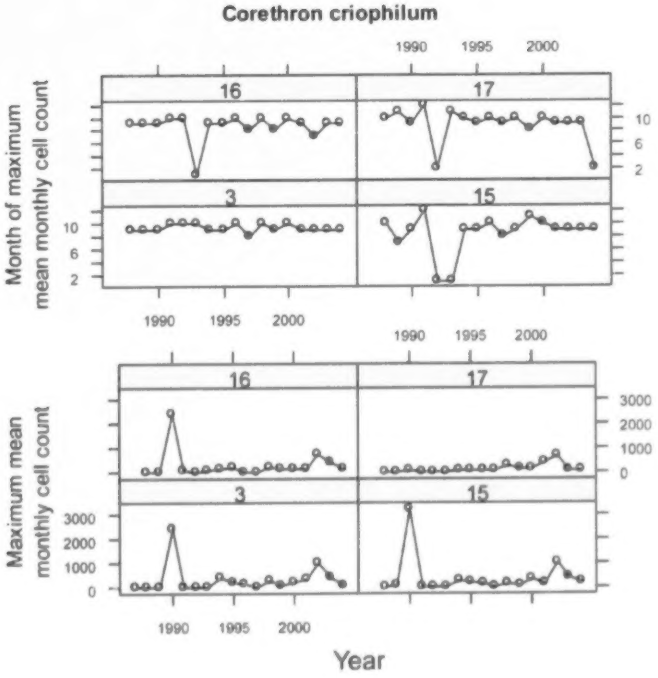


Fig. 2. Time series plots (1987-2004) showing the month of maximum mean monthly cell counts and the maximum mean monthly cell counts at four monitoring sites (16, 17, 3, 15) for each species analyzed.



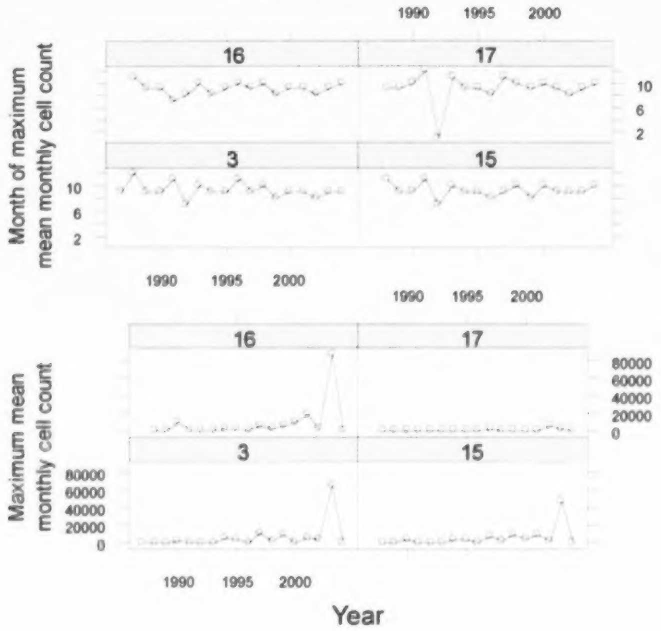
Chaetoceros socialis



Corethron criophilum

Fig. 2 continued.

Ditylum brightwellii



Eucampia zodiacus

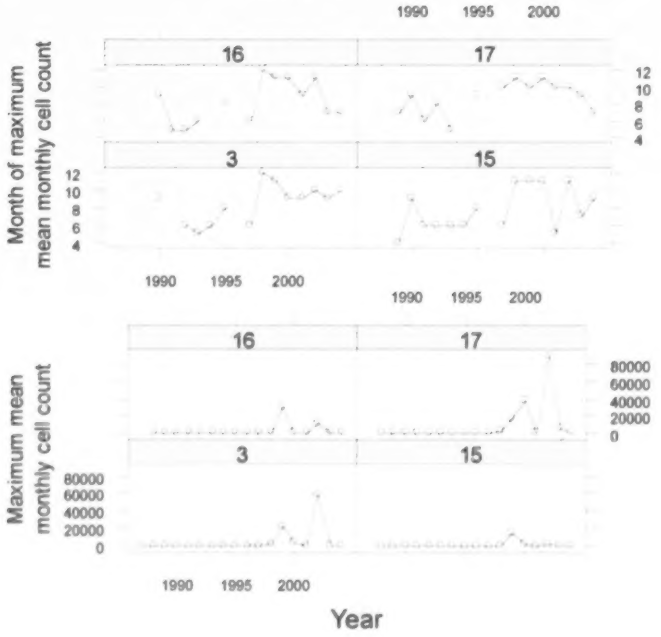
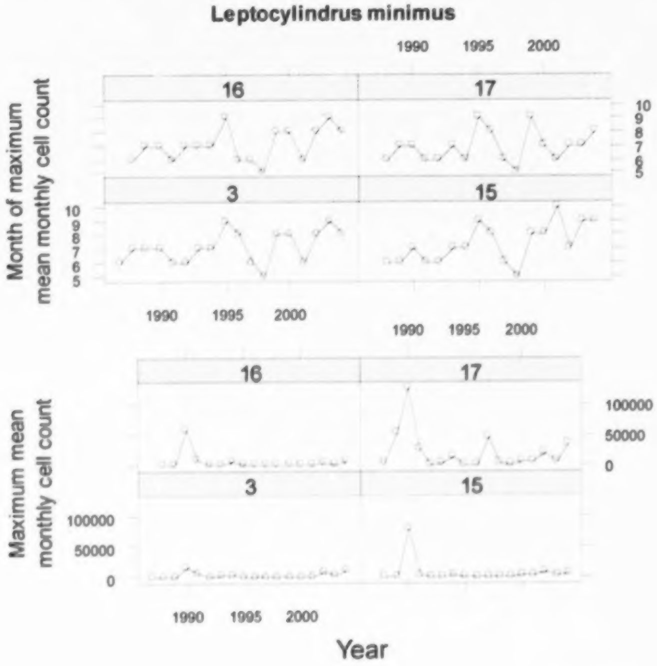
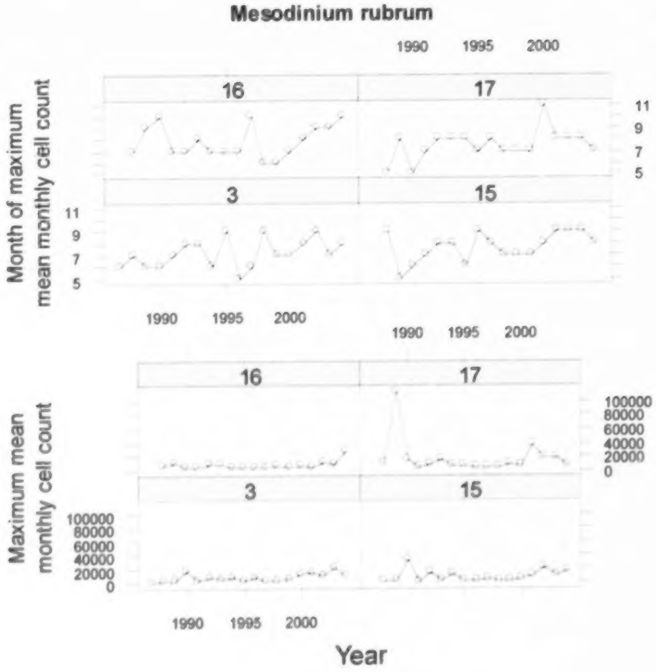


Fig. 2 continued.



Leptocylindrus minimus



Mesodinium rubrum

Fig. 2 continued.

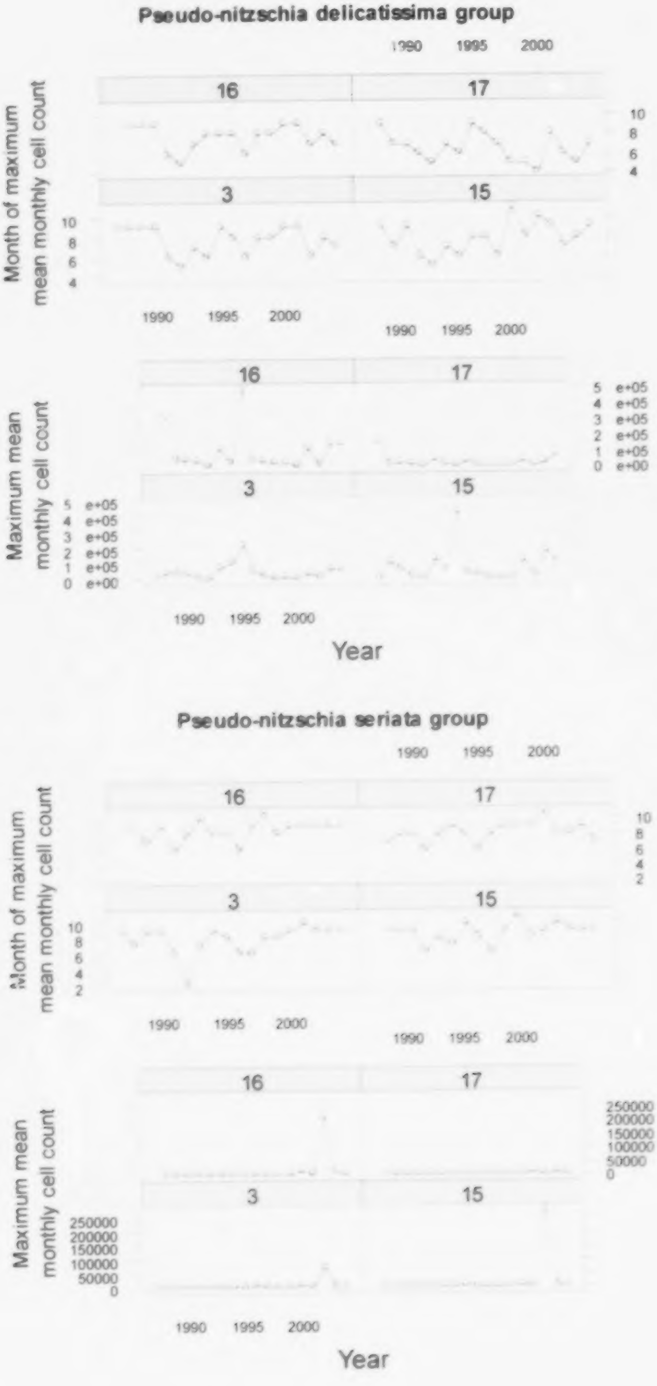


Fig. 2 continued.

Appendix 4
Retrospective analyses of monitoring data

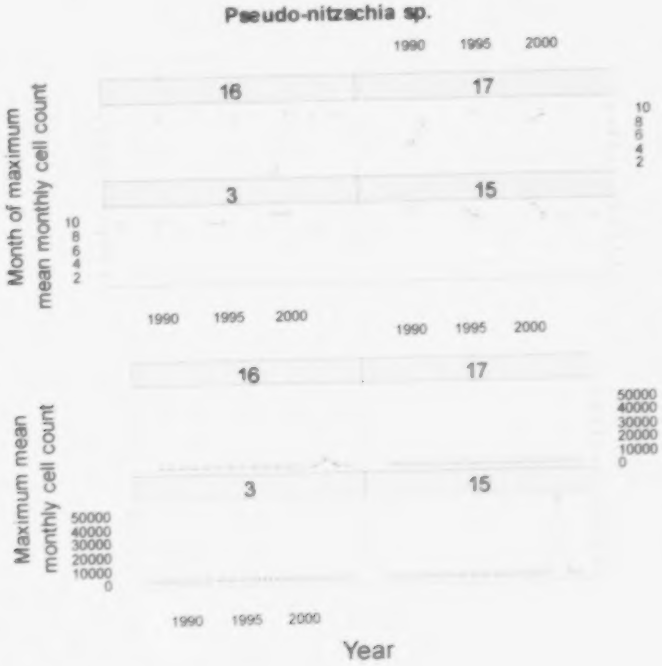


Fig. 2 concluded.

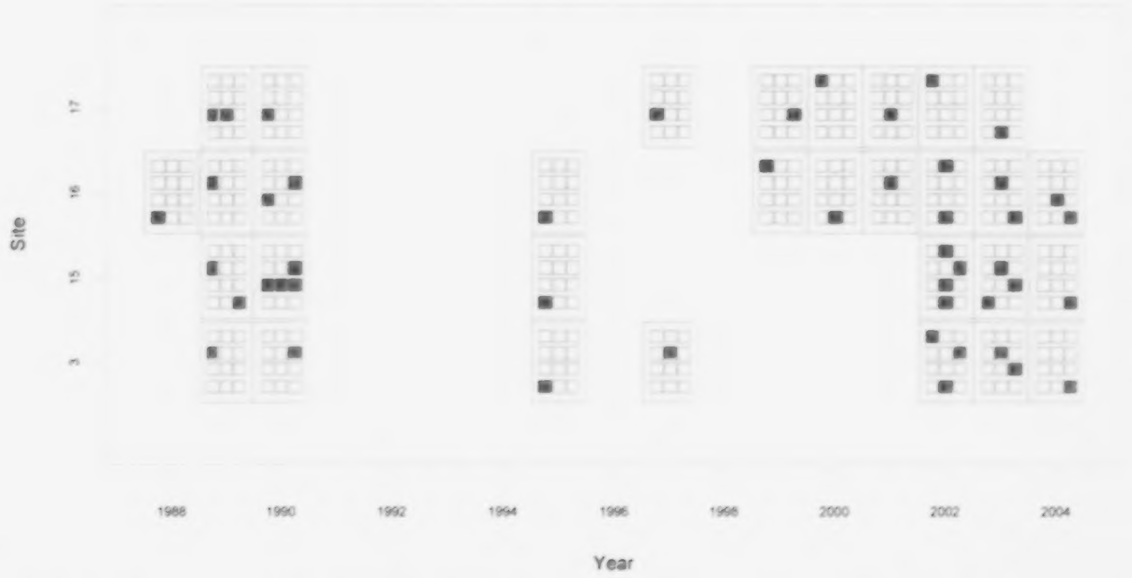


Fig. 3. Occurrence of blooms of each species by site and year. The cells within each pictograph represent the 11 harmful algal species which were studied. The cells represent, from left to right: bottom row – *Pseudo-nitzschia delicatissima* group, *Pseudo-nitzschia seriata* group, *Alexandrium fundyense*; next row up – *Leptocylindrus minimus*, *Mesodinium rubrum*, *Chaetoceros socialis*; next row up – *Chaetoceros convolutus*, *Ditylum brightwellii*, *Corethron criophilum*; top row – *Eucampia zodiacus*, *Pseudo-nitzschia sp.*, no data in the last cell. Pictographs are only shown for the site-year combinations where at least one of the 11 species bloomed.

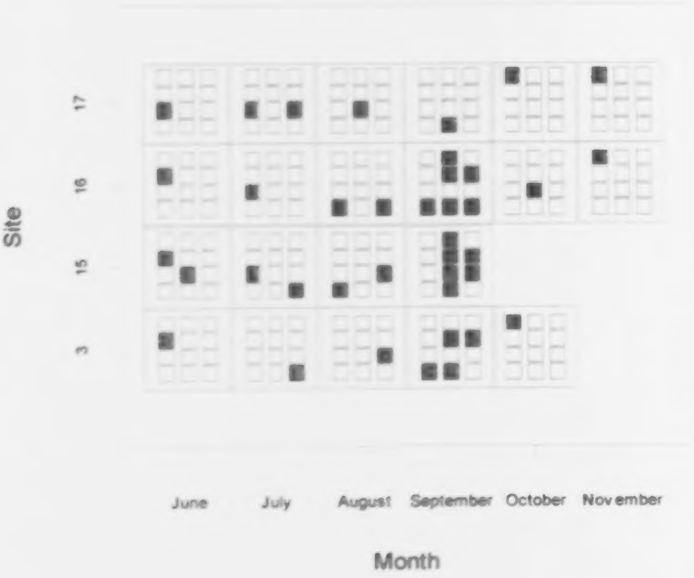


Fig. 4. Occurrence of blooms of each species by site and month. The cells within each pictograph represent the 11 harmful algal species which were studied, as in Fig. 3. Pictographs are only shown for the site-month combinations where at least one of the 11 species bloomed.

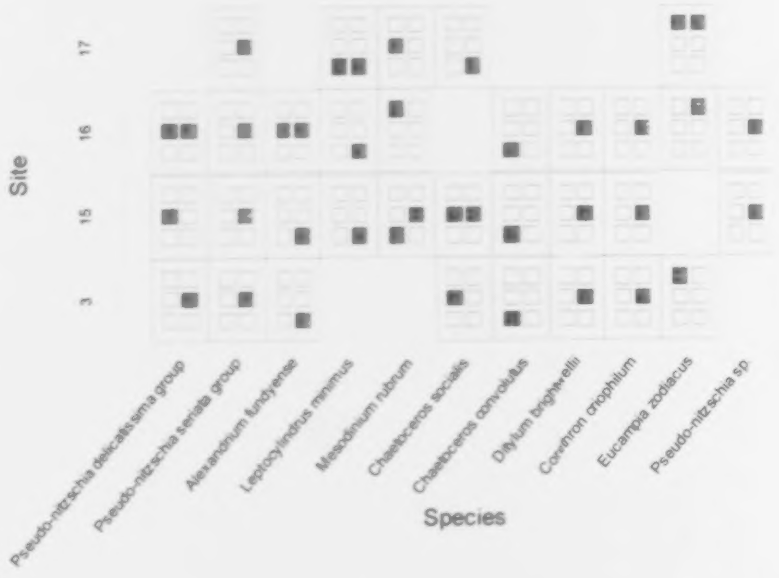


Fig. 5. Months of occurrence of blooms for each site and species. The cells in each pictograph represent the months when bloom events occurred. The cells represent, from left to right: bottom row – June, July; middle row – August, September; top row – October, November. Pictographs are only shown for the site-species combinations where at least one bloom occurred.

USE OF A WATER CIRCULATION MODEL TO PREDICT THE MOVEMENTS OF PHYTOPLANKTON BLOOMS AFFECTING SALMON FARMS IN THE GRAND MANAN ISLAND AREA, SOUTHWESTERN NEW BRUNSWICK

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Introduction

The spatial and temporal origins of water that flows through a fish farm can be estimated using a customized version of an existing numerical model of the mean tidal circulation of the southwestern New Brunswick (SWNB) area (Greenberg et al. 2005). This information can be used to predict the likelihood of a phytoplankton bloom being transported via water currents to or from a farm within one or more tidal cycles. We used this methodology to predict movements of phytoplankton blooms in the vicinity of salmon farms in the Grand Manan Island area. This methodology can also be applied to other fish farming areas in SWNB.

Estimated Tidal Excursion Areas of Fish Farms in the Grand Manan Island Area

As part of another ACRDP project (Fish Health and Oceanography), the tidal circulation model was used to predict the likelihood that diseases such as infections salmon anemia (ISA) could be transported via surface water currents during one tidal cycle, among salmon farms in the Grand Manan Island area (Page et al. 2005; Chang et al. 2006). These predictions can also serve to predict the likelihood that a phytoplankton bloom affecting one farm could impact other farms within one tidal cycle.

The model runs only included the most important tidal component in this geographical area, the M_2 tide (the principal lunar semi-diurnal constituent). Particles were released from a 200 × 200 m grid of 36 points located at the approximate centre of each farm site. The particles were released and maintained at 1 m below the sea surface. Particles were released from each grid point at hourly intervals, from hour 0 to hour 11 (12 particles released from each grid point, for a total of 432 particles), and each particle was tracked for one tidal cycle (12.4 h); particles stopped moving if they hit land or exposed intertidal areas. The tidal excursion area was estimated as the area covered by the tracks of all 432 particles during one tidal cycle.

The predicted tidal excursion areas for all farms in the eastern and southern Grand Manan Island areas are shown in Fig. 1. Figure 2 is a close-up map showing the tidal excursion area for one farm (MF-172); for maps of the tidal excursion areas of other farms in the Grand Manan Island area, as well as details on the methodology, see Page et al. (2005) and Chang et al. (2006). We determined the overlaps of each farm's tidal excursion area with other farms (Table 1) and with other farms' tidal excursion areas (Table 2).

The estimated tidal excursion areas of the five farms in the Long Island area are small, extending a short distance southward. Because of the close proximity of these five farms, a bloom affecting one farm would affect other farms in this area. The tidal excursion areas of the southernmost farms in this area (MF-002 and MF-349) come close to farm sites in the Ross Island area, and overlap the tidal excursion area of one farm in that area (MF-282). The tidal excursion areas of farms in the Ross Island area are larger, extending mostly southward. The tidal excursion areas of two of these farms (MF-172 and MF-300) overlap farm sites in the White Head Island area, and also overlap the tidal excursion areas of farms in the White Head Island and Long Pond Bay areas. The tidal excursion areas of farms in the White Head Island area are large, extending to the southwest (away from farming areas) and westward toward, but not touching, farm sites in the Long Pond Bay area, but overlapping the tidal excursion areas of some farms in that area. The tidal excursion areas of farms in the Long Pond Bay area do not overlap farm sites in any other area, but do overlap the tidal excursion areas of farms in both the Seal Cove and White Head Island areas. The tidal excursion area of one farm in the Seal Cove area (MF-270) overlaps two farm sites in the Long Pond Bay area (MF-408 and MF-491), and the tidal excursion areas of farms MF-270 and MF-003 overlap the tidal excursion areas of farms in the Long Pond Bay area.

These results suggest that phytoplankton blooms could be transported via water currents among some farms in the eastern and southern Grand Manan Island areas during one tidal cycle. The highest risk is for bloom movements among farms within the same sub-area, but there could be some bloom movements between farms in different sub-areas, such as from farms in the Ross Island area toward White Head Island farms, and from one Seal Cove area farm toward Long Pond Bay area farms.

Use of the Tidal Circulation Model to Predict Movements of Blooms in Nearshore and Offshore Areas around Grand Manan Island over 8 Tidal Cycles

To examine the movements of potential algal blooms over larger spatial and temporal scales (i.e. not just movements to or from existing fish farms over one tidal cycle), we used the same circulation model to release particles from a grid of evenly-spaced points (750 m between points) around Grand Manan Island (Fig. 3), and we tracked the particles over a longer period (eight tidal cycles, approximately 100 h or 4 d). In addition, the model runs in this study included multiple tidal constituents (not just the M_2 tide), as well as a wind component. As in the earlier study, the particles were released and maintained at 1 m below the sea surface, and the particles were released from each grid point at hourly intervals over a 12-h period (12 particles released from each grid point).

We then determined which particles intersected each farm site and how long after release the intersection occurred. Figure 3 shows the release points of all particles which intersected at least one farm. Figure 4 shows the release points of all particles that intersected at least one farm in each sub-area (Long Island, Ross Island, White Head Island, Long Pond Bay, and Seal Cove). Example detailed results for one farm (MF-172) are shown in Fig. 5. For this farm, most intersecting particles originated to the north, but some particles originated to the east, south, and southwest. However, the few intersecting particles from the southwest could reach the farm faster than particles originating a similar distance away from other directions. Further details on the methodology and complete results for this component are published in a separate technical report (Chang et al. 2007).

The results indicated that farms in the Long Island area were most likely to be affected by blooms originating in the immediate vicinity of the farms or just to the north, and that the blooms would be slow moving. Farms in the Ross Island area would also be most likely affected by blooms originating in the immediate area of the farms or from the north, but the blooms could originate further away and could move faster; also, some blooms could be transported to Ross Island area farms from areas slightly to the east and south. Farms in the White Head Island area could be affected by relatively fast-moving blooms originating over a wide area, including the Long Pond Bay and Seal Cove areas to the west, the Ross Island area to the north, and offshore areas to the northeast. Farms in the Long Pond Bay area could be affected mainly by blooms originating within the Long Pond Bay area, the Seal Cove area, and south of the Seal Cove area. Farms in the Seal Cove area could be affected mainly by blooms originating in the Seal Cove area and to the south.

The results of this study show the predicted movements of surface water which could transport blooms toward fish farms. The actual risk of a farm being affected by a bloom depends on whether or not a bloom occurs along the predicted water movement pathways, as well as how the bloom develops while being transported. The results from this study only indicate the likely movements (as predicted by the model) of blooms during the time frame of this study (i.e. up to eight tidal cycles or 4 d). This time frame was considered useful for contingency planning at farms. For example, if a bloom was observed at a location from which, according to the model, it would likely be transported to the farm in 4 d, the farm could prepare for management actions (such as changes to smolt transfer, feeding, or harvesting schedules), while at some shorter time interval, management actions would actually be implemented.

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Page, F.H., Chang, B.D., Losier, R.J., Greenberg, D.A., Chaffey, J.D., and McCurdy, E.P. 2005. Water circulation and management of infectious salmon anemia in the salmon aquaculture industry of southern Grand Manan Island, Bay of Fundy. Can. Tech. Rep. Fish. Aquat. Sci. 2595: iii + 78 p.

Table 1. Overlaps (indicated by shaded squares) of model-derived tidal excursion areas with finfish farm sites in the eastern and southern Grand Manan Island areas. Data previously reported in Chang et al. 2006.

Overlaps of originating farm tidal excursion areas with receiving farm sites			**Originating farm**																				
			Long I. area					Ross I. area				White Head I.			Long Pond Bay area				Seal Cove area				
			MF-002	MF-213	MF-349	MF-350	MF-368	MF-172	MF-282	MF-298	MF-300	MF-316	MF-381	MF-416	MF-303	MF-403	MF-408	MF-491	MF-003	MF-202	MF-270	MF-292	MF-413
Receiving farm	Long I. area	MF-002	■	■	■	■	■																
		MF-213		■																			
		MF-349	■		■		■																
		MF-350	■	■		■																	
		MF-368		■			■																
	Ross I. area	MF-172						■	■		■												
		MF-282							■	■	■												
		MF-298								■													
		MF-300							■	■	■												
	White Head I.	MF-316						■			■	■	■										
		MF-381						■			■	■	■										
		MF-416										■	■	■									
	Long Pond Bay area	MF-303													■								
		MF-403														■	■	■					
		MF-408														■	■	■			■		
		MF-491																■			■		
	Seal Cove area	MF-003																	■		■		
		MF-202																		■		■	
		MF-270																	■		■		
		MF-292																		■		■	
		MF-413																					■

Table 2. Overlaps (indicated by shaded squares) among model-derived tidal excursion areas of finfish farm sites in the eastern and southern Grand Manan Island areas. Data previously reported in Chang et al. 2006.

Overlaps of originating farm tidal excursion areas with receiving farm tidal excursion areas			Originating farm																				
			Long I. area					Ross I. area				White Head I.			Long Pond Bay area				Seal Cove area				
			MF-002	MF-213	MF-349	MF-350	MF-368	MF-172	MF-282	MF-298	MF-300	MF-316	MF-381	MF-416	MF-303	MF-403	MF-408	MF-491	MF-003	MF-202	MF-270	MF-292	MF-413
Receiving farm	Long I. area	MF-002	▨	▨	▨	▨	▨		▨														
		MF-213	▨	▨	▨	▨	▨																
		MF-349	▨	▨	▨	▨	▨		▨														
		MF-350	▨	▨	▨	▨																	
		MF-368	▨	▨	▨		▨																
	Ross I. area	MF-172						▨	▨		▨	▨	▨	▨		▨	▨						
		MF-282	▨		▨			▨	▨	▨	▨												
		MF-298							▨	▨	▨												
		MF-300						▨	▨	▨	▨	▨	▨	▨		▨	▨						
	White Head I.	MF-316						▨			▨	▨	▨	▨		▨	▨						
		MF-381						▨			▨	▨	▨	▨		▨	▨						
		MF-416						▨			▨	▨	▨	▨		▨	▨						
	Long Pond Bay area	MF-303													▨	▨	▨	▨					
		MF-403						▨			▨	▨	▨	▨	▨	▨	▨	▨	▨		▨		
		MF-408						▨			▨	▨	▨	▨	▨	▨	▨	▨	▨		▨		
		MF-491													▨	▨	▨	▨			▨		
	Seal Cove area	MF-003														▨	▨		▨		▨		
		MF-202																		▨		▨	
		MF-270														▨	▨	▨	▨		▨		
		MF-292																		▨		▨	▨
		MF-413																				▨	▨

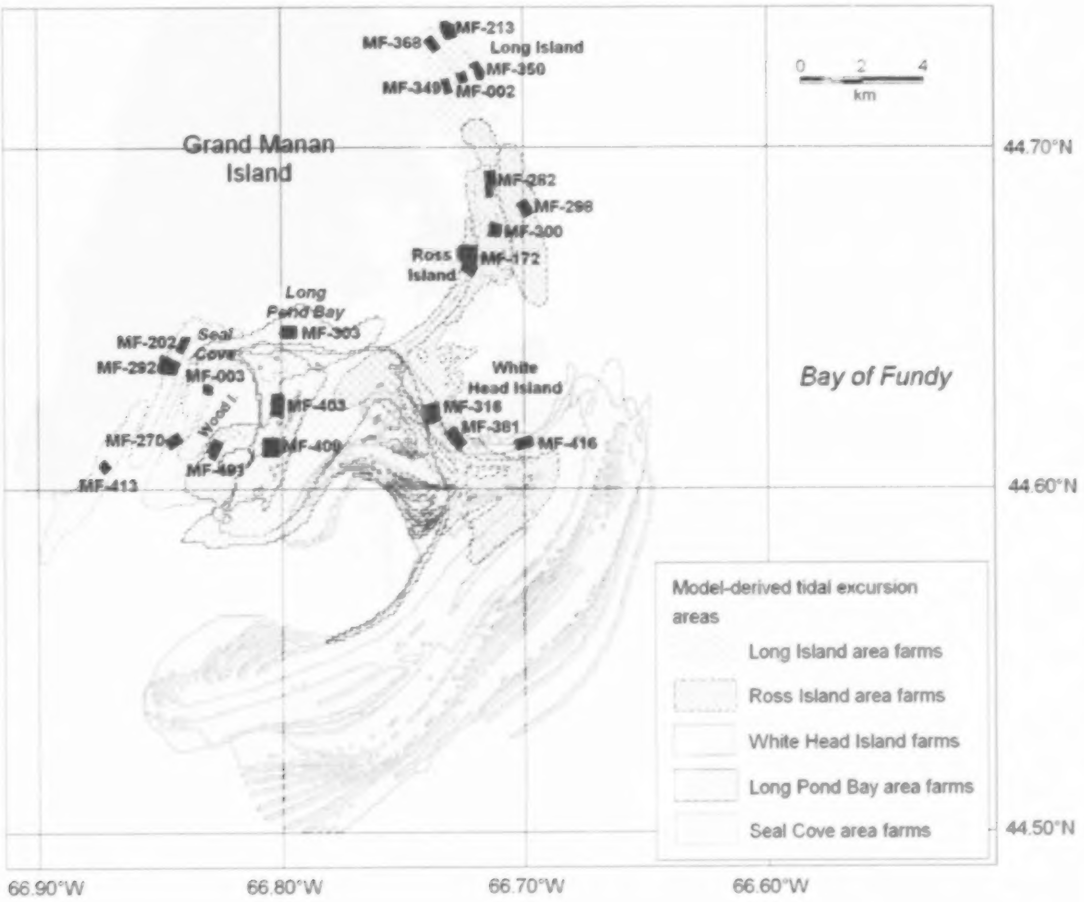

MF-213
MF-368
Long Island
MF-350
MF-349
MF-002
0 2 4
km
Grand Manan Island
44.70°N
MF-282
MF-298
MF-300
Ross Island
MF-172
Long Pond Bay
MF-303
MF-202
Seal Cove
MF-292
MF-003
Wood I.
MF-403
White Head Island
MF-316
MF-381
MF-416
Bay of Fundy
MF-270
MF-400
MF-491
MF-413
44.60°N
Model-derived tidal excursion areas
Long Island area farms
Ross Island area farms
White Head Island farms
Long Pond Bay area farms
Seal Cove area farms
44.50°N
66.90°W
66.80°W
66.70°W
66.60°W

Fig. 1. Map showing model-derived tidal excursion areas of all finfish farms in the eastern and southern Grand Manan Island areas. Data previously reported in Chang et al. (2006).

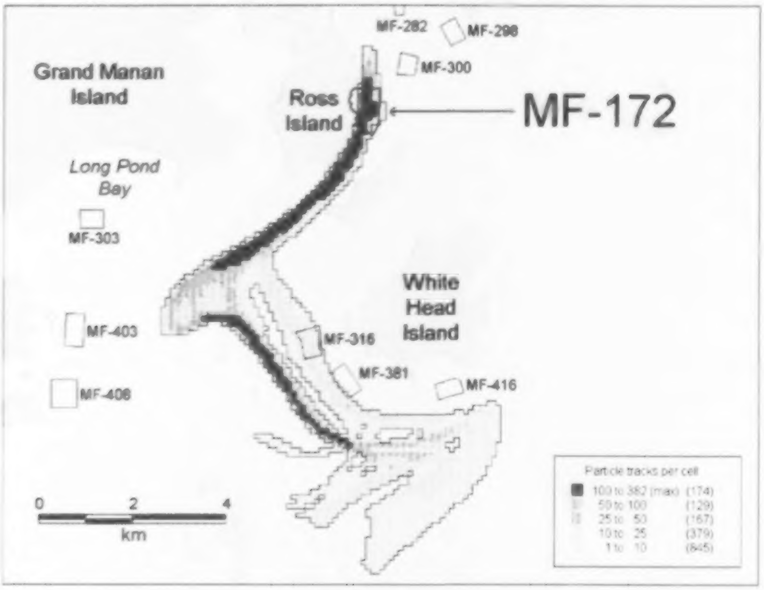

MF-282
MF-298
MF-300
Grand Manan Island
Ross Island
MF-172
Long Pond Bay
MF-303
MF-403
MF-408
White Head Island
MF-316
MF-381
MF-416
0
2
4
km
Particle tracks per cell
100 to 382 (max) (174)
50 to 100 (129)
25 to 50 (167)
10 to 25 (379)
1 to 10 (845)

Fig. 2. Model-derived tidal excursion area of finfish farm MF-172, eastern Grand Manan Island area. The shading represents the number of model-derived particle tracks intersecting 100 × 100 m square cells. Thirty-six particles were released from a 200 × 200 m grid located at the centre of the farm, at hourly intervals over a 12-h period (see text for details). Each particle was tracked for one tidal excursion (12.42 h) or until it stopped upon hitting the shore, whichever came first. Farm sites are shown as small polygons. Numbers in parentheses in the legend are the numbers of cells within each range of particle track counts. Figure reproduced from Chang et al. (2006).

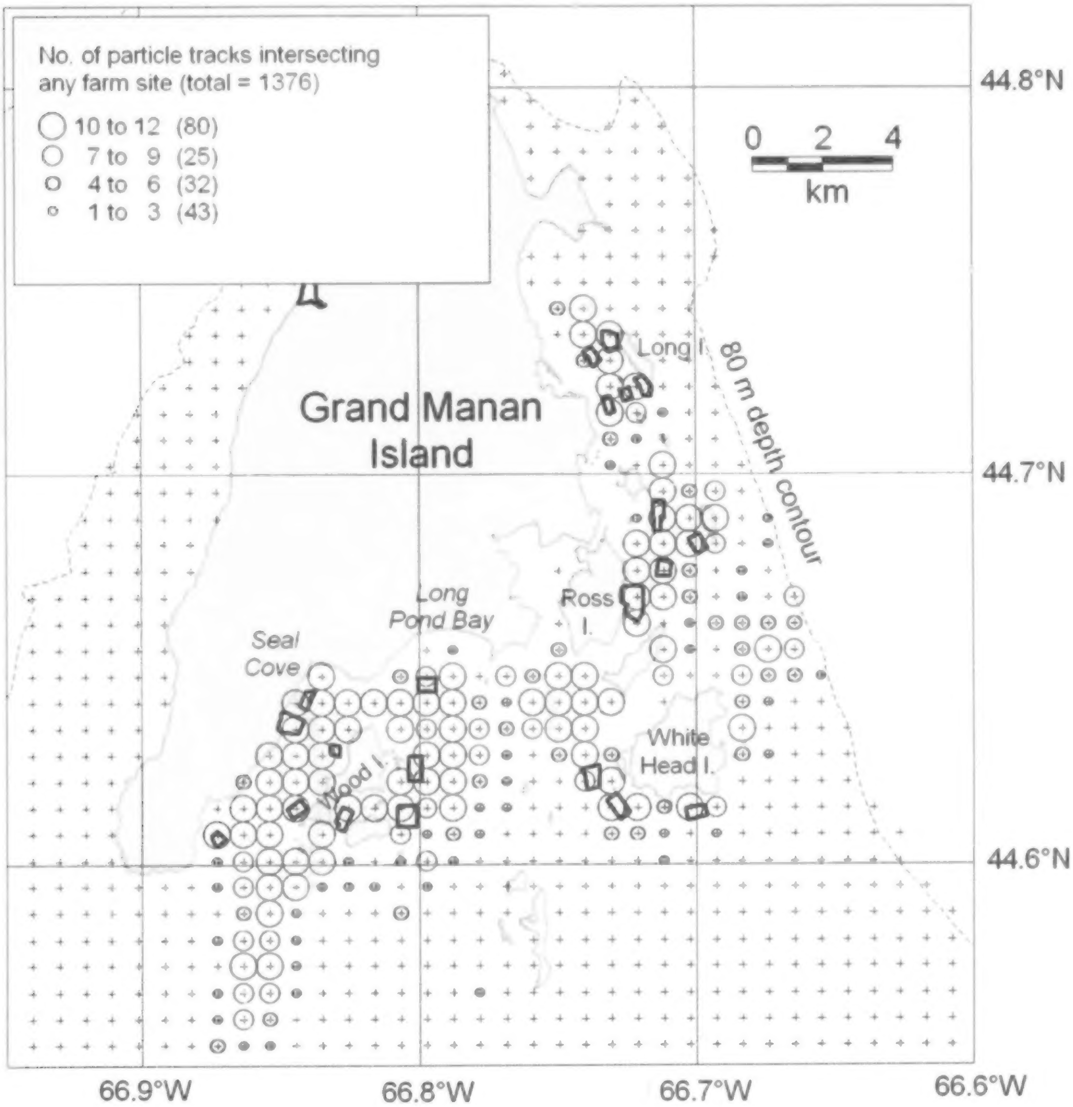

No. of particle tracks intersecting any farm site (total = 1376)
10 to 12 (80)
7 to 9 (25)
4 to 6 (32)
1 to 3 (43)
0 2 4
km
Grand Manan Island
Long I.
80 m depth contour
Ross I.
Long Pond Bay
Seal Cove
Wood I.
White Head I.
44.8°N
44.7°N
44.6°N
66.9°W
66.8°W
66.7°W
66.6°W

Fig. 3. Map of the model particle release grid around Grand Manan Island, Bay of Fundy, showing the release locations of all model particles, indicating which locations released particles which intersected at least one finfish aquaculture farm site within 100 h after release (eight tidal cycles). Small crosses indicate all model particle release locations (a total of 659 release points, separated by 750 m in the north-south and east-west directions). Twelve particles were released from each point, at hourly intervals. Circles of varying sizes indicate the release locations of particles which intersected at least one farm site (see map legend; the numbers in parentheses in the legend represent the number of release points within each category). Small polygons (thick, black outlines) indicate finfish farm sites.

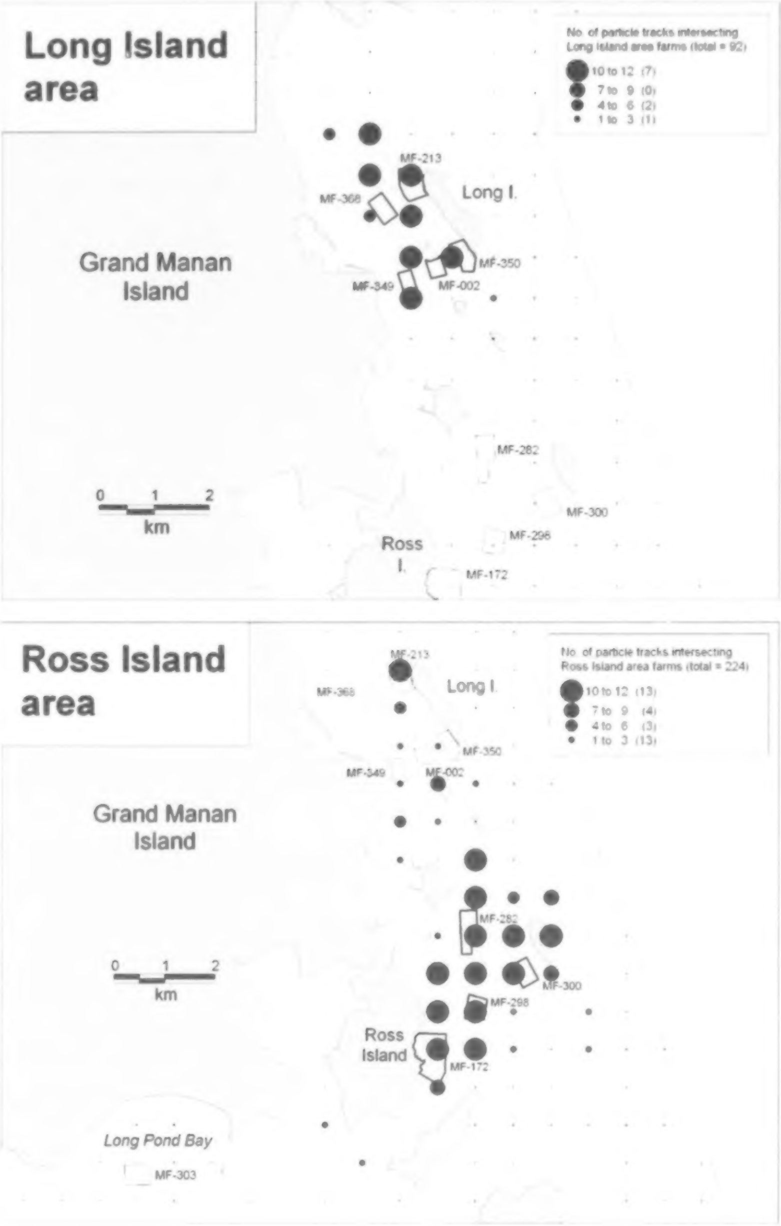
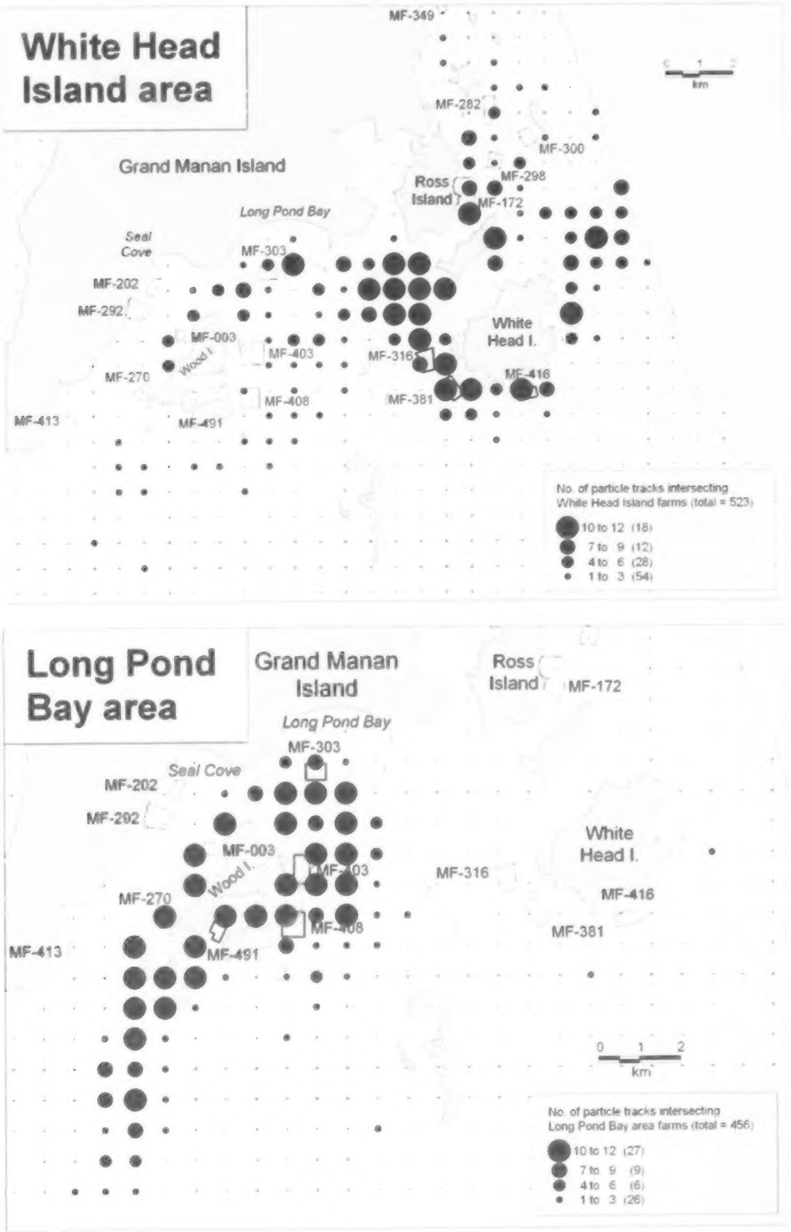

Long Island area
No. of particle tracks intersecting Long Island area farms (total = 92)
10 to 12 (7)
7 to 9 (0)
4 to 6 (2)
1 to 3 (1)
MF-213
MF-368
Long I.
Grand Manan Island
MF-350
MF-349
MF-002
MF-282
0 1 2
km
MF-300
Ross I.
MF-298
MF-172
Ross Island area
No. of particle tracks intersecting Ross Island area farms (total = 224)
10 to 12 (13)
7 to 9 (4)
4 to 6 (3)
1 to 3 (13)
MF-213
MF-368
Long I.
MF-350
MF-349
MF-002
Grand Manan Island
MF-282
0 1 2
km
MF-300
MF-298
Ross Island
MF-172
Long Pond Bay
MF-303

Fig. 4. Map showing release points of model particles whose tracks intersected farm sites in the Long Island, Ross Island, White Head Island, Long Pond Bay, and Seal Cove areas within 100 h after release (eight tidal cycles). Farms are shown as small polygons; small crosses represent all particle release points; black circles indicate release points of particles whose tracks intersected the farm sites indicated with thick outlines; the size of the circles represents the number of particles originating from this point which intersected the farm site (see map legend); the numbers in parentheses in the legend represent the number of release points in each category.



White Head Island area
Grand Manan Island
Long Pond Bay
Seal Cove
Ross Island
White Head I.
Wood I.
MF-349
MF-282
MF-300
MF-298
MF-172
MF-303
MF-202
MF-292
MF-003
MF-403
MF-316
MF-270
MF-416
MF-408
MF-381
MF-413
MF-491
0 1 2
km
No. of particle tracks intersecting White Head Island farms (total = 523)
10 to 12 (18)
7 to 9 (12)
4 to 6 (28)
1 to 3 (54)
Long Pond Bay area
Grand Manan Island
Ross Island
MF-172
Long Pond Bay
MF-303
Seal Cove
MF-202
MF-292
MF-003
MF-403
MF-316
White Head I.
MF-270
Wood I.
MF-416
MF-408
MF-381
MF-413
MF-491
0 1 2
km
No. of particle tracks intersecting Long Pond Bay area farms (total = 456)
10 to 12 (27)
7 to 9 (9)
4 to 6 (6)
1 to 3 (26)

Fig. 4 continued.

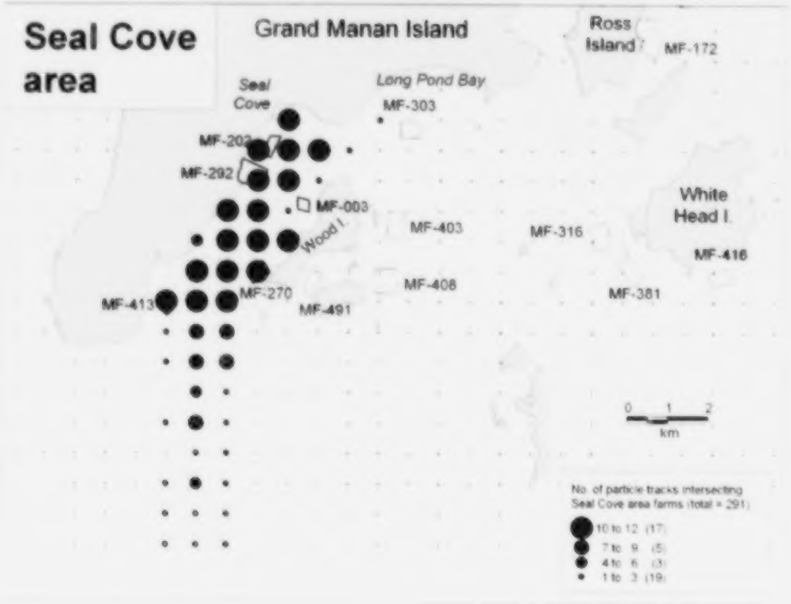

Seal Cove area
Grand Manan Island
Ross Island
MF-172
Seal Cove
Long Pond Bay
MF-303
MF-202
MF-292
MF-003
Wood I.
MF-403
MF-316
White Head I.
MF-416
MF-270
MF-413
MF-491
MF-408
MF-381
0 1 2
km
No. of particle tracks intersecting Seal Cove area farms (total = 291)
10 to 12 (17)
7 to 9 (5)
4 to 6 (3)
1 to 3 (19)

Fig. 4 concluded.

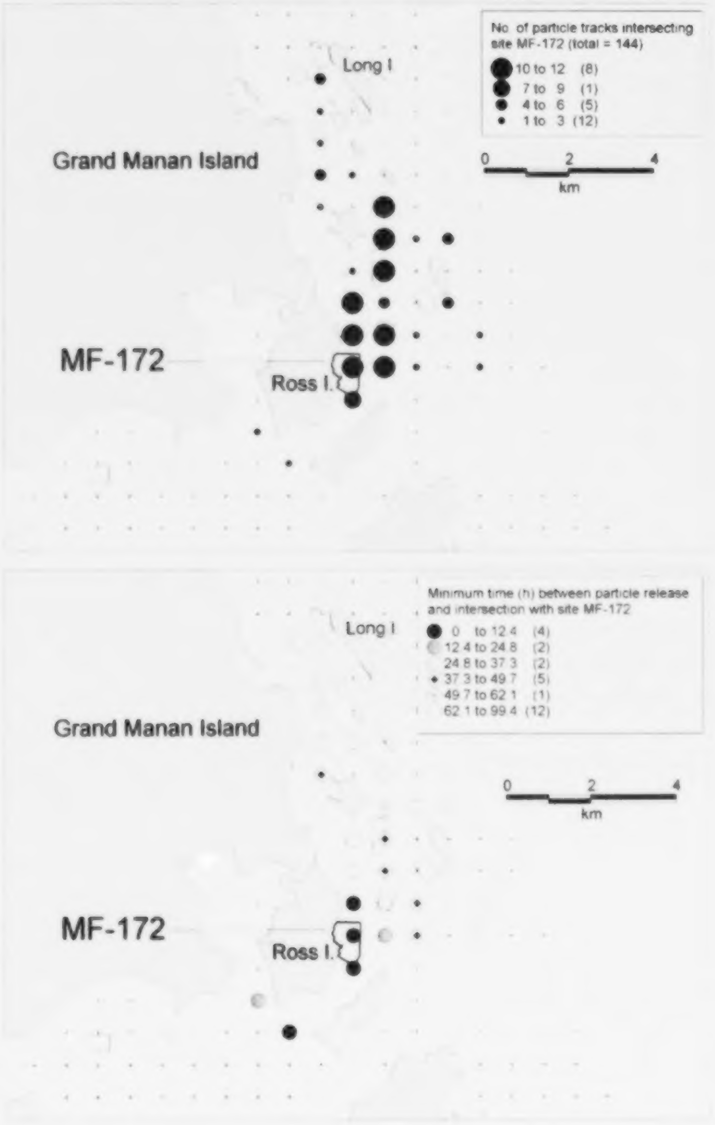

No. of particle tracks intersecting site MF-172 (total = 144)
● 10 to 12 (8)
● 7 to 9 (1)
● 4 to 6 (5)
• 1 to 3 (12)
0
2
4
km
Long I
Grand Manan Island
MF-172
Ross I.
Minimum time (h) between particle release and intersection with site MF-172
● 0 to 12.4 (4)
12.4 to 24.8 (2)
24.8 to 37.3 (2)
• 37.3 to 49.7 (5)
49.7 to 62.1 (1)
62.1 to 99.4 (12)
0
2
4
km
Long I
Grand Manan Island
MF-172
Ross I.

Fig. 5. Maps showing the release points of model particles whose tracks intersected farm site MF-172 at Ross Island within 100 h after release (eight tidal cycles). Farms are shown as small polygons; small crosses represent all particle release points; circles indicate the release points of particles whose tracks intersected farm site MF-172. Top map: the size of the circles represents the number of particles originating from each point which intersected farm site MF-172 (see map legend). Bottom map: the shading of the circles represents the shortest time between a particle's release and its intersection with farm site MF-172 (where there was more than one intersecting particle from the same release point, the shortest time between particle release and farm site intersection was used; see map legend). The numbers in parentheses in the legends represent the number of release points in each category.

DEPLOYMENT OF A LIGHT SENSOR ARRAY FOR THE DETECTION OF PHYTOPLANKTON BLOOMS

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Introduction

The use of passive optical instruments has been suggested as a method for detecting algal blooms, especially where traditional phytoplankton sampling programs are costly or impractical (Cullen et al. 1997). Sunlight hitting the water surface will be attenuated with depth. Part of this attenuation is due to the physical properties of pure water. Another part of the attenuation is due to substances in the water, including both dissolved and particulate materials; phytoplankton would be part of the latter. Therefore, measuring the amount of water reaching different depths can provide information that can be related to phytoplankton abundance.

Passive optical instruments have the potential for continuous data collection, thus providing much more frequent data than traditional water sampling techniques. It is recognized, however, that traditional water sampling is required to correlate the optical data with phytoplankton abundance. Optical instruments can detect changes in chlorophyll levels in the water, and thus may be correlated with total phytoplankton abundance, but cannot identify individual species.

In this study, we deployed an optical sensor to measure the attenuation of light near a salmon farm in southwestern New Brunswick (SWNB), in order to examine the potential of this technology for detecting phytoplankton blooms. Similar equipment has been used to measure seston depletion at a mussel farm in Nova Scotia (Ibarra 2003). The optical sensor was deployed at a site participating in the enhanced monitoring component (see Appendix 3), in order to allow us to compare the light attenuation data with phytoplankton abundance. Additional phytoplankton sampling at discrete depths was also conducted as part of this component.

Methods

We deployed a Tethered Attenuation Coefficient Chain Sensor (TACCS), manufactured by Satlantic Inc. (Fig. 1). We initially attempted to deploy the equipment at a farm in the eastern Grand Manan Island area in the fall of 2004, but because of delays in obtaining some components and difficulties encountered in installing and operating the equipment, we were not successful. We were able to deploy the equipment successfully at a site (farm 377) in Passamaquoddy Bay (Fig. 1) in June-August 2005.

The TACCS consists of a surface buoy and a chain of sensors suspended vertically below the buoy (Fig. 2). The buoy was attached to mooring lines at the fish farm. Batteries or buoys were changed at approximately weekly intervals. Sensors were cleaned whenever batteries or buoys were changed.

The sensors recorded the downwelling irradiance (E_d, in units of $\mu W \cdot cm^{-2} \cdot nm^{-1}$) at 0, 2, 4, 8, and 16 m below the sea surface. For this study we measured the irradiance for light of wavelength 490 nm, which is near the middle of the range for active photosynthesis by marine algae (Parsons et al. 1984). The TACC recorded data every second for 20 s every 10 min, from approximately 05:00-20:00 Atlantic Daylight Time. For our analyses, we used the mean values for each 20-s recording period. E_d values less than 0.1 $\mu W \cdot cm^{-2} \cdot nm^{-1}$ were excluded from the analyses, since they were considered to be within the noise levels in low light conditions.

The diffuse attenuation coefficient for downwelling irradiance (K_d, in units of m^{-1}) was calculated as the slope of $\ln(E_d)$ vs. depth (Cullen et al. 1997). K_d can be considered to be the sum of K_w, the term for pure water, and K_{bio}, the term for all biogenic components, including algae, non-algal cells (viruses, heterotrophic bacteria, and other small heterotrophs), detritus, dissolved organic colored matter (DOCM), and possibly bubbles (Morel and Maritorena 2001). For 490 nm wavelength light, the value of K_w has been estimated as 0.016 60 m^{-1} (Morel and Maritorena 2001), so K_{bio} can be calculated as $K_d - 0.016\,60$.

Because the attenuation of light can be due to factors other than phytoplankton, we need to compare optical readings when no phytoplankton blooms were occurring with readings during blooms of different intensities. The expectation is that irradiance levels (E_d) will decrease during blooms, while the attenuation coefficient (K_{bio}) would increase (compared to the levels under similar solar conditions but without a bloom) due to light absorption by the phytoplankton. Water samples for phytoplankton analyses were taken at the sensor site at depths of 1, 3, 6, and 12 m (mid-way between optical sensor depths) on 24 August 2005. Surface water and 10-m vertical tow samples were also taken at this site in 2005 as part of the enhanced monitoring component of this project (see Appendix 3).

Results

General

The TACCS equipment was deployed from 9 June to 31 August 2005 at the site in Passamaquoddy Bay. During this 84-d period, we obtained good quality data, with $E_d \geq 0.1$ $\mu W \cdot cm^{-2} \cdot nm^{-1}$ at mid-day (from 11:00-14:00 h) on 57 d for depths 0-8 m and 51 d for the 16-m sensor. Data obtained on 5 d was excluded due to abnormally low readings, possibly due to sensor fouling. Data was not obtained on some days due to equipment maintenance or equipment problems (e.g. some water leakage into the surface buoy housing occurred on at least two occasions).

Irradiance and attenuation coefficients

Examples of daily plots of irradiance (E_d) vs. time and K_{bio} vs. time are shown in Fig. 3. The expected diel variation in E_d was observed, with maximum readings generally near mid-day. Also as expected, the light intensity decreased with depth. The values of K_{bio} showed no clear trends during the day or with depth.

Plots of daily mean K_{bio} values (Fig. 4) showed somewhat elevated values (except at 16 m) in mid-June. There appeared to be a slight downward trend in values during late June through July. Values in August were somewhat variable, especially from 13-31 August; this latter period also had 9 d when no data was recorded or data was unusable (values that were clearly abnormal).

Phytoplankton samples

Water samples for phytoplankton analyses were taken at different depths at this site on 18 and 24 August 2005. No significant numbers of any species were observed in the samples collected on 18 August. Cell counts for different species on 24 August are shown in Table 1. The most common species found was *Chaetoceros socialis*. The numbers of all species observed were relatively low (compared to numbers in bloom conditions) and indicated an overall decrease in abundance with depth.

Phytoplankton counts from water samples collected as part of the enhanced monitoring component of this project are shown in Fig. 5. The only species to show elevated levels during the period of TACCS deployment were *Pseudo-nitzschia delicatissima* group (in mid to late June) and *C. socialis* (in early August).

Discussion

The values of the attenuation component (K_{bio}) were similar in range to that found by Ibarra (2003) using similar equipment in nearshore waters at Ship Harbour, Nova Scotia. Unfortunately, phytoplankton levels were generally low at our site during the deployment, so we did not obtain sufficient data to allow us to correlate the irradiance data with phytoplankton abundance. Ideally, we would have had several large bloom events at different times during the deployment, and these would be correlated with changes in light attenuation. It is possible that the slightly elevated K_{bio} values in early June were related to the bloom of *P. delicatissima* that was observed at this site at the time, and there was some indication of increasing K_{bio} values in early August when the bloom of *C. socialis* occurred (although in the latter case the K_{bio} values were still relatively low in early August when the cells counts were high). Further deployments, especially during phytoplankton blooms, would be required to fully test the usefulness of this equipment for detecting blooms. Future deployments should also be coupled with water sampling for determination of the levels of chlorophyll and other pigments, as well as phytoplankton analysis.

References

Cullen, J.J., Ciotti, A.M., Davis, R.F., and Lewis, M.R. 1997. Optical detection and assessment of algal blooms. Limnol. Oceanogr. 42: 1223-1239.

Ibarra, D.A. 2003. Estimation of seston depletion by cultured mussels (*Mytilus* spp.) using measurements of diffuse attenuation of solar irradiance from optical moorings. Thesis (M.Sc.) Dalhousie University, Halifax, NS.

Morel, A. and Maritorena, S. 2001. Bio-optical properties of oceanic waters: a reappraisal. J. Geophys. Res. 106(C4): 7163-7180.

Parsons, T.R., Takahashi, M., and Hargrave, B. 1984. Biological oceanographic processes, 3rd ed. Pergamon Press, Oxford, UK.

Table 1. Counts of phytoplankton species (organisms·L^{-1}) found in water samples collected at different depths at the TACCS deployment site in Passamaquoddy Bay on 24 August 2005.

	Depth (m)			
Species	1	3	6	12
Chaetoceros socialis	12 427	24 710	13 728	4 191
Dictyocha speculum	12 861	3 035	1 445	867
Heterocapsa triquetra	27 166	2 457	1 156	0
Mesodinium rubrum	10 260	4 769	3 035	578
Pseudo-nitzschia spp.	1 156	1 301	1 590	2 023
All others	31 501	13 005	14 161	14 739
Totals	95 370	49 275	35 114	22 398

Appendix 6

Light sensor array deployment

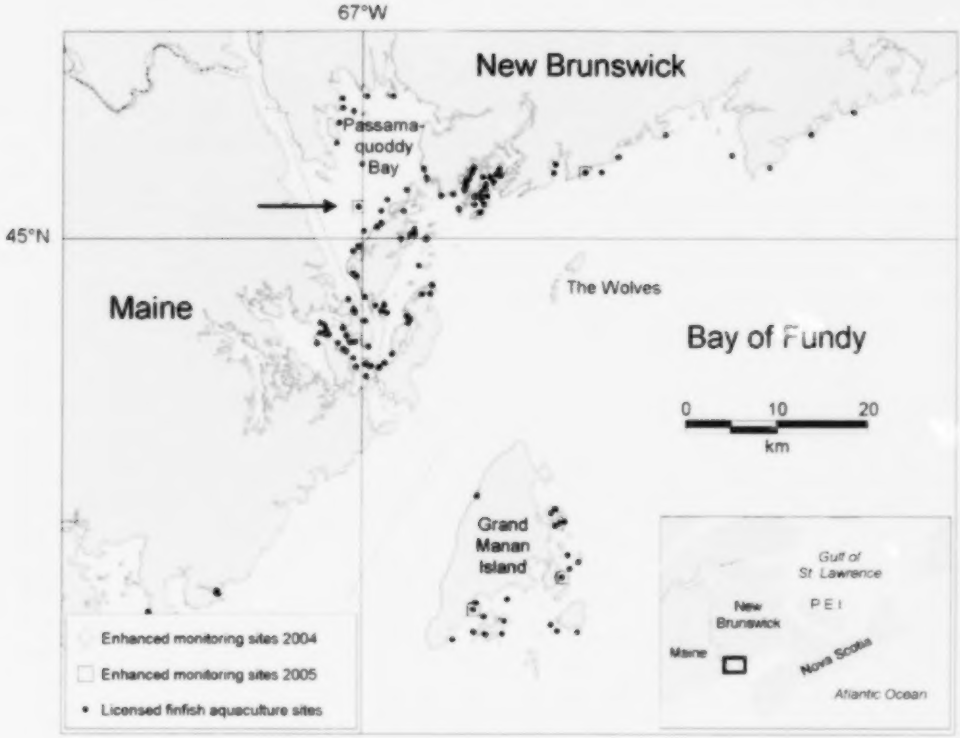

67°W
45°N
New Brunswick
Passamaquoddy Bay
Maine
The Wolves
Bay of Fundy
0
10
20
km
Grand Manan Island
○ Enhanced monitoring sites 2004
☐ Enhanced monitoring sites 2005
• Licensed finfish aquaculture sites
Gulf of St. Lawrence
New Brunswick
P.E.I.
Maine
Nova Scotia
Atlantic Ocean

Fig. 1. Map of SWNB. The arrow indicates the location of the Tethered Attenuation Coefficient Chain Sensor (TACCS) deployment in July-September 2005.

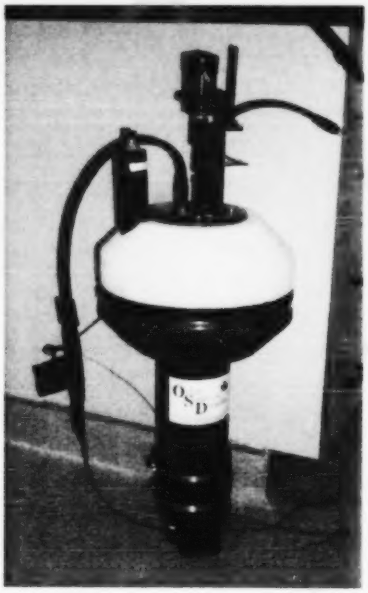


Fig. 2. The Tethered Attenuation Coefficient Chain Sensor (TACCS): surface buoys (left); subsurface sensor chain (right).

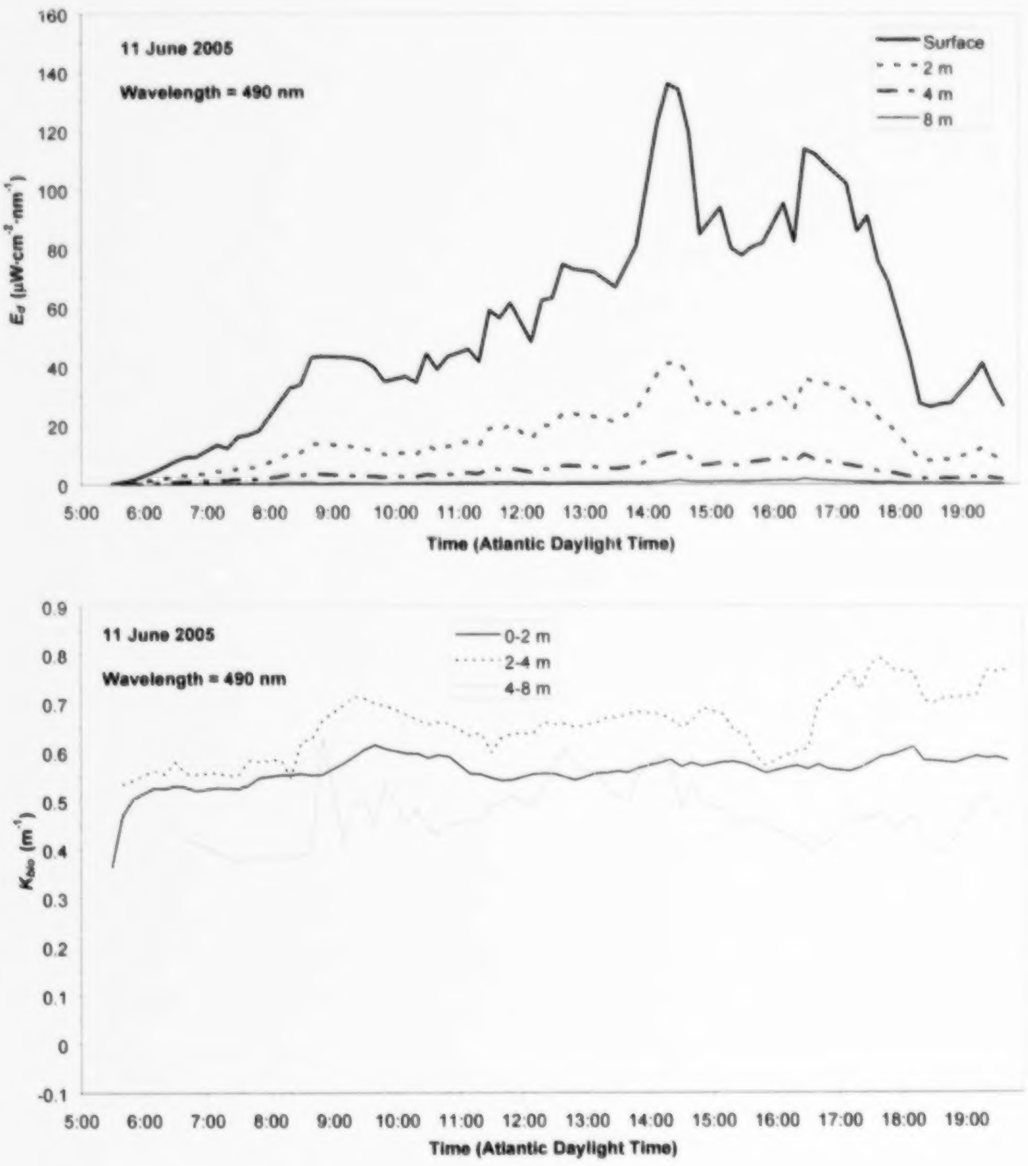


Fig. 3. Plots of data collected for light of wavelength = 490 nm on selected dates by the Tethered Attenuation Coefficient Chain Sensor (TACCS) deployed at a finfish farm site in Passamaquoddy Bay. Top: downward irradiance (E_d) vs. time. Bottom: the attenuation coefficient for downward irradiance for biogenic components (K_{bio}) vs. time.

Appendix 6
Light sensor array deployment

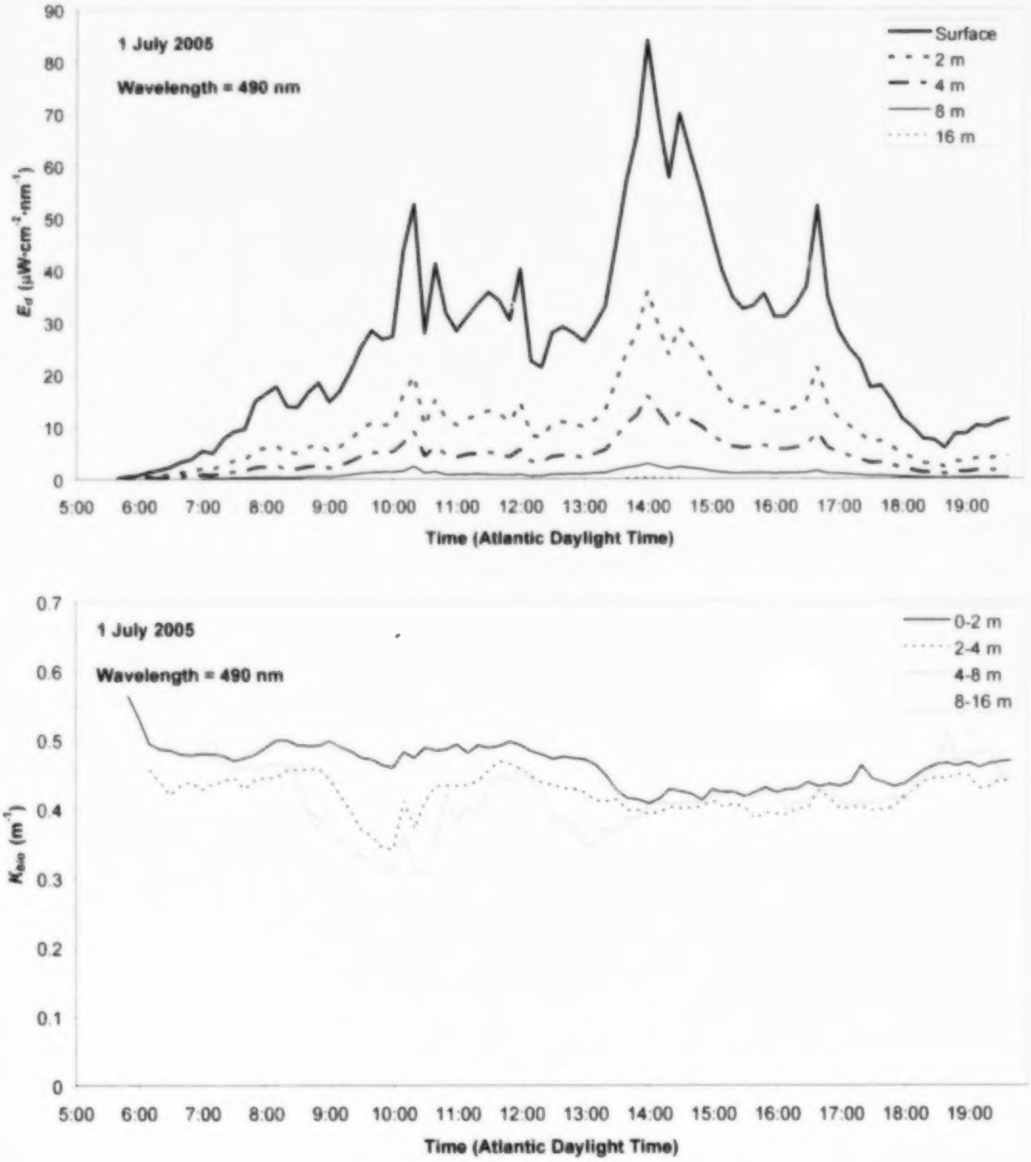
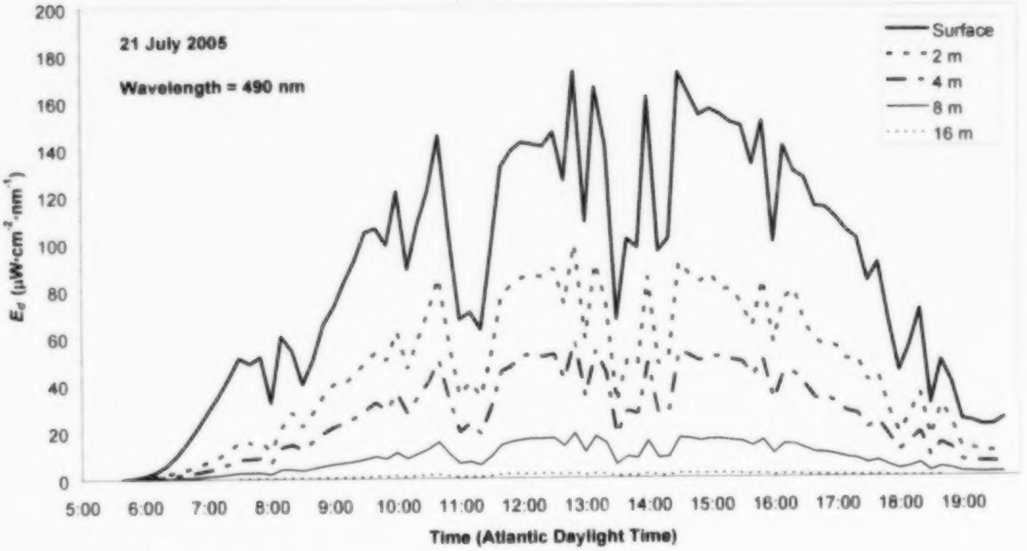


Fig. 3 (continued).

Appendix 6
Light sensor array deployment



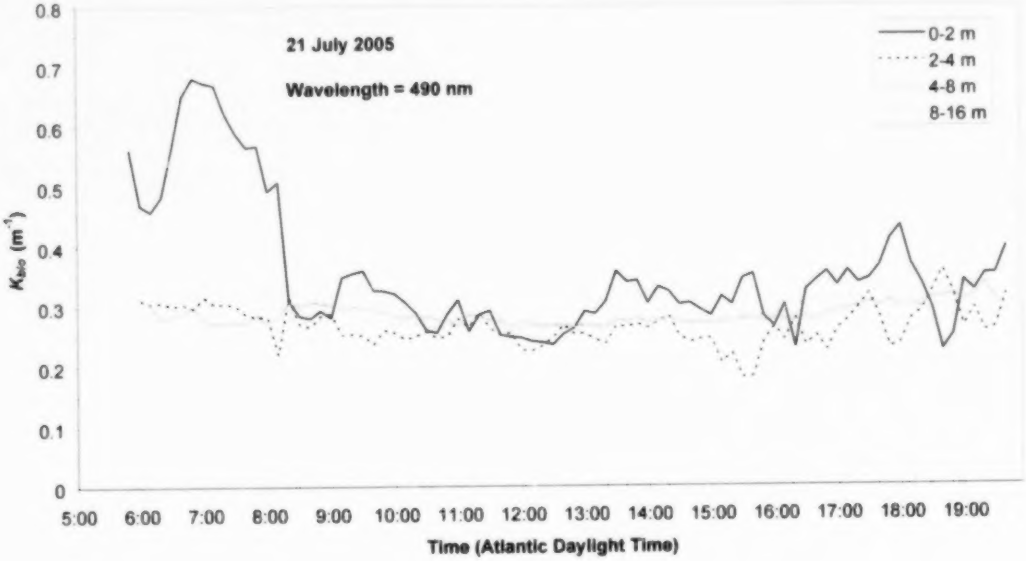


Fig. 3 (continued).

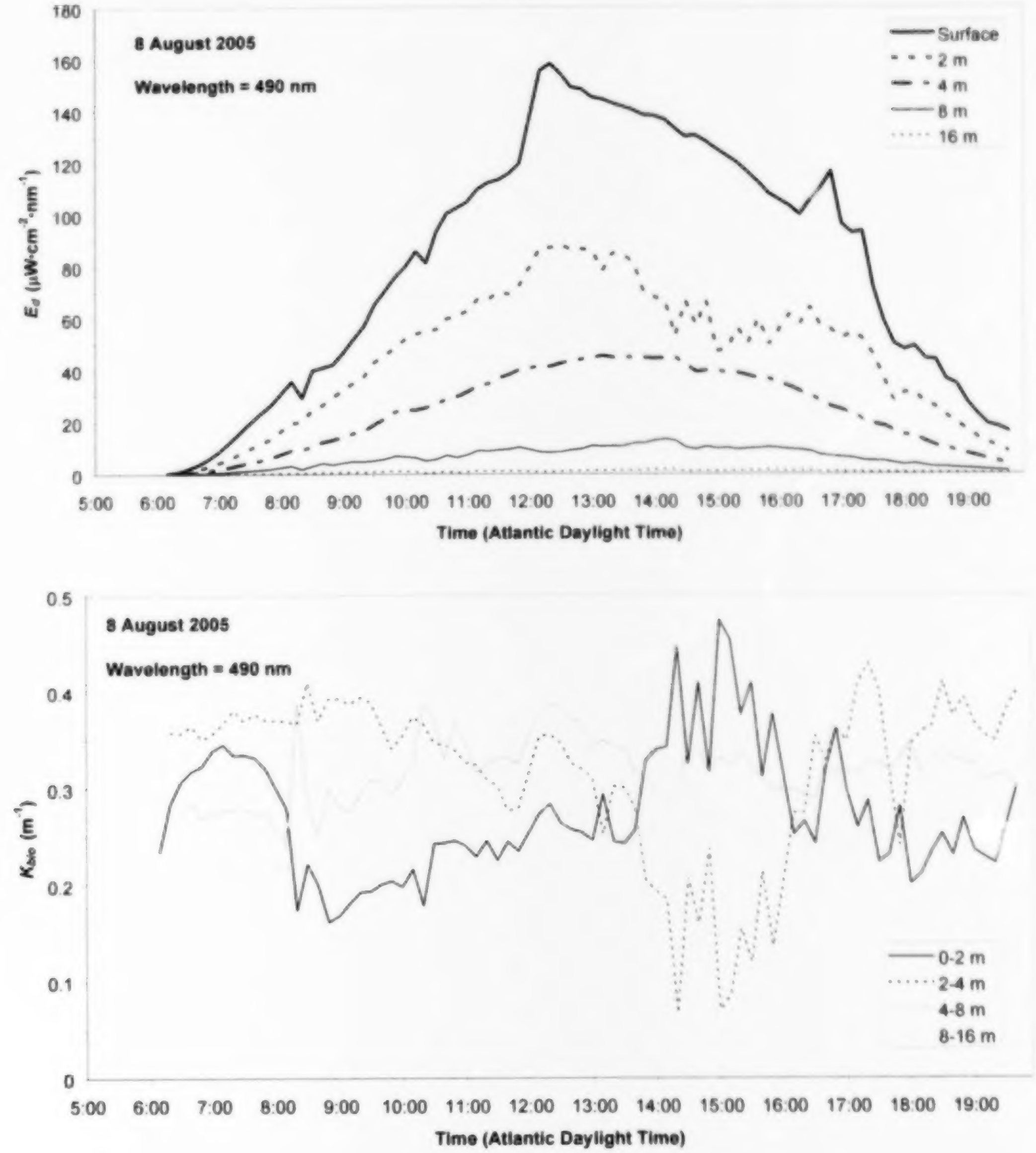
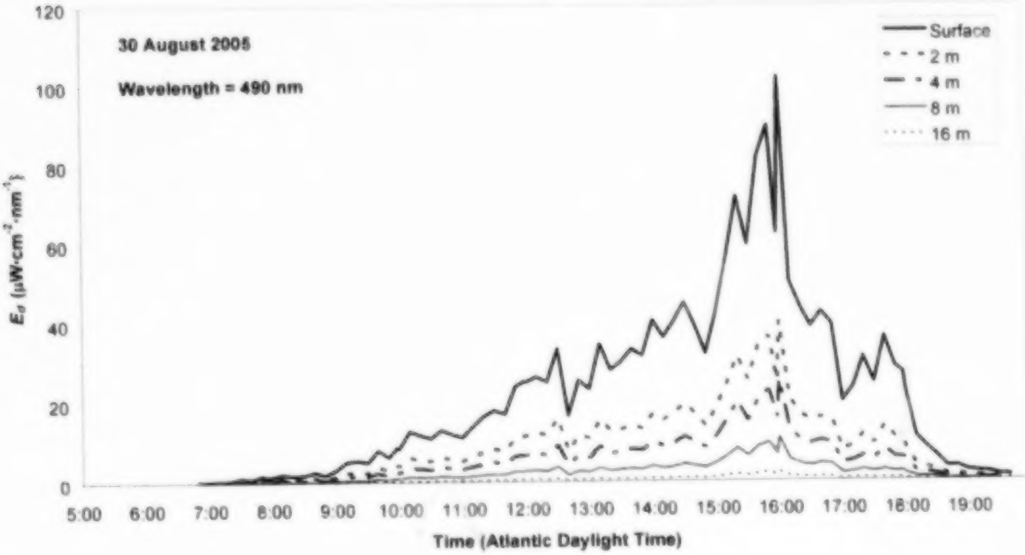


Fig. 3 (continued).

Appendix 6
Light sensor array deployment



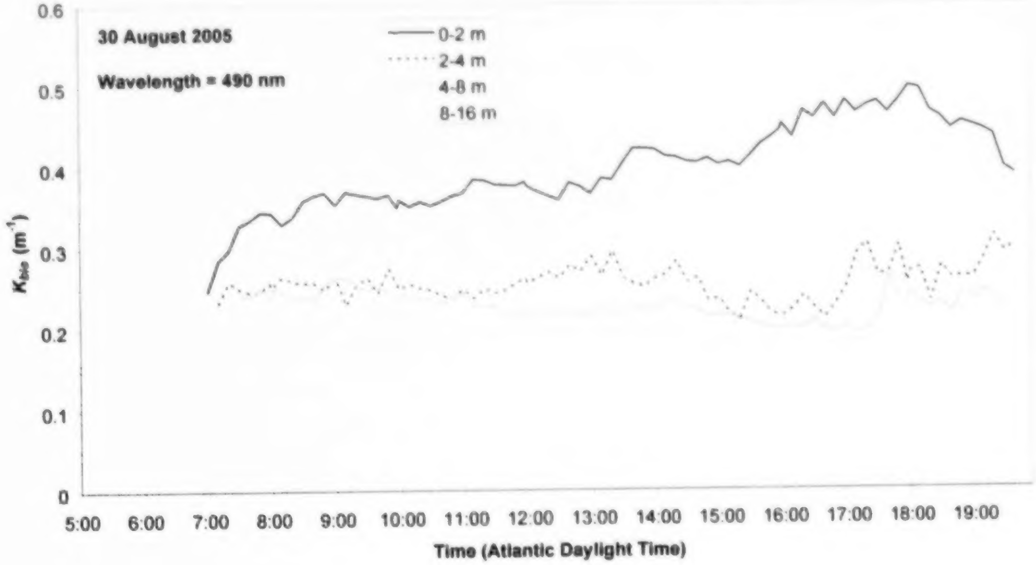


Fig. 3 (concluded).

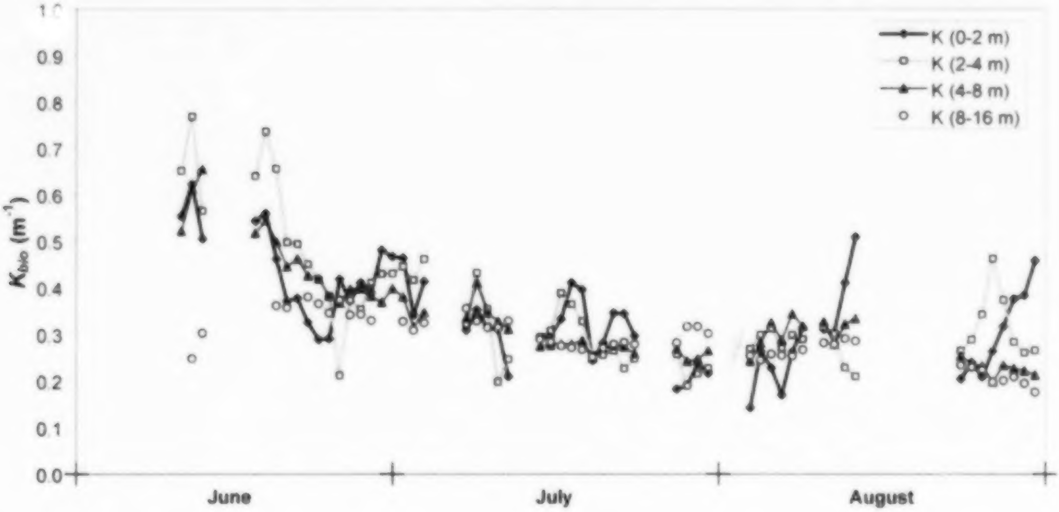


Fig. 4. Plots of the attenuation coefficient for downward irradiance for biogenic components (K_{bio}) between different depths vs. date in June-August 2005. K_{bio} values are means for the period 11:00-14:00 on each day.

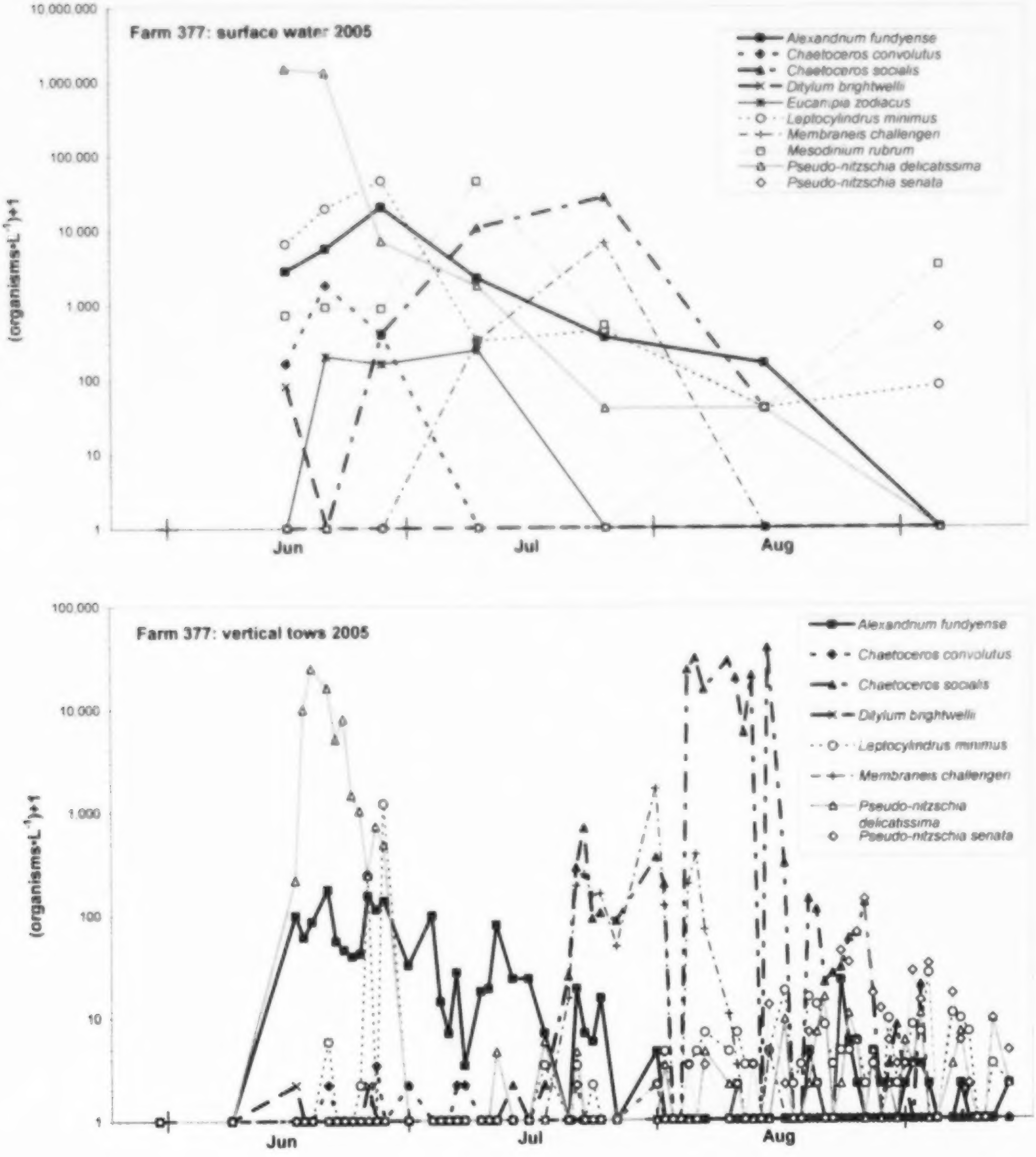


Fig. 5. Phytoplankton abundance in surface water (top) and 0-11 m vertical tow (bottom) samples at the TACCS deployment site (farm 377) in Passamaquoddy Bay in 2005.

UTILITY OF SATELLITE-BASED REMOTE-SENSING OF OCEAN COLOR FOR PROVIDING EARLY WARNING OF PHYTOPLANKTON BLOOMS FOR FISH FARMERS IN SOUTHWESTERN NEW BRUNSWICK

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Historical Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite images (1997-2004) were examined for evidence of being able to detect and track phytoplankton blooms within the lower Bay of Fundy. An example of a SeaWiFS ocean color image in our study area is shown in Fig. 1.

Figure 2 shows an example of the time-series (1998-2004) of satellite data we were able to extract for the Wolves Islands area. There are approximately two satellite passes per day, which would give us the potential for >5000 images over the 7 yr. We were able to retrieve only about 700 useful images for the Wolves area, which is only 13% of the potential. This was primarily due to clouds and foggy conditions.

In coastal waters, the satellite imagery does not give us accurate chlorophyll estimates due to interference from colored dissolved organic matter (CDOM), suspended sediments, and bottom reflection in very shallow waters. For that reason, we had to correct the image data using measured surface chlorophyll data. This was difficult due to the limited chlorophyll data available and constraints for matching the measured chlorophyll with the satellite pass (the data we used had to be within a few hours of the satellite pass). Figure 3 gives an example of satellite data and measured surface chlorophyll data at the Wolves in 2000 and 2001. We were able to recover about 30 calibration data points from the Prince 5 and the Wolves monitoring stations (Fig. 4) and even with that, the regression was not that great ($r^2<50\%$). Nonetheless, we used this to correct the satellite data to give us more realistic chlorophyll levels. Based on this analysis, about 50% of the signal the satellite retrieved was not chlorophyll.

The corrected satellite chlorophyll data were then compared with measured *Alexandrium fundyense* concentrations. Figure 5 shows that, in general, the timing of events coincided, but satellite chlorophyll levels and *A. fundyense* abundances did not match well. Note particularly the low chlorophyll levels in 2004 when *A. fundyense* levels were highest on record. Closer examination of the time-series of chlorophyll and *A. fundyense* abundance shows that *A. fundyense* growth generally came after the first of two major chlorophyll peaks (Fig. 6). In 1998 *A. fundyense* growth occurred immediately after the chlorophyll event; in 2001, growth was much later than the chlorophyll peak; in 2004 there was not much variability in chlorophyll, yet record high *A. fundyense* numbers. The median (for 1998-2004) time delay between the chlorophyll peaks and the *A. fundyense* peaks was about 17 days, but ranged from 3-50 d. These results suggest that current satellite data products in coastal waters may be able to track bulk chlorophyll levels, but not *A. fundyense* blooms.

An example of the spatial information that the satellite data provides (best images recovered during July-August 2004) is given in Fig. 7. The spatial resolution (1.5 x 1.5 km) is adequate for characterization of only very large-scale patches of phytoplankton. There is no evidence from these images of the large *A. fundyense* bloom that was occurring at the time, although the images do show the relatively distinctive biological enhancement of the Fundy "gyre."

Only when *A. fundyense* reaches abundances that can be seen as chlorophyll levels above the very high background chlorophyll levels of the Bay of Fundy will ocean color satellite images in their present configuration be useful for tracking harmful algal blooms (HABs). Although the satellite data products we have available currently may not serve as a practical early warning for HABs, they may be useful, along with HAB observations, in developing a better understanding of the link between HABs and the background phytoplankton communities.

Complete results for this component are published in a separate report (Harrison et al. 2007).

Reference

Harrison, W.G., Martin, J.L., and Maass, H. 2007. Phytoplankton early warning approaches for finfish aquaculture in southwestern New Brunswick: Utility of satellite-based remote-sensing of ocean colour. Can. Tech. Rep. Fish. Aquat. Sci. 2706: iii + 29 p.

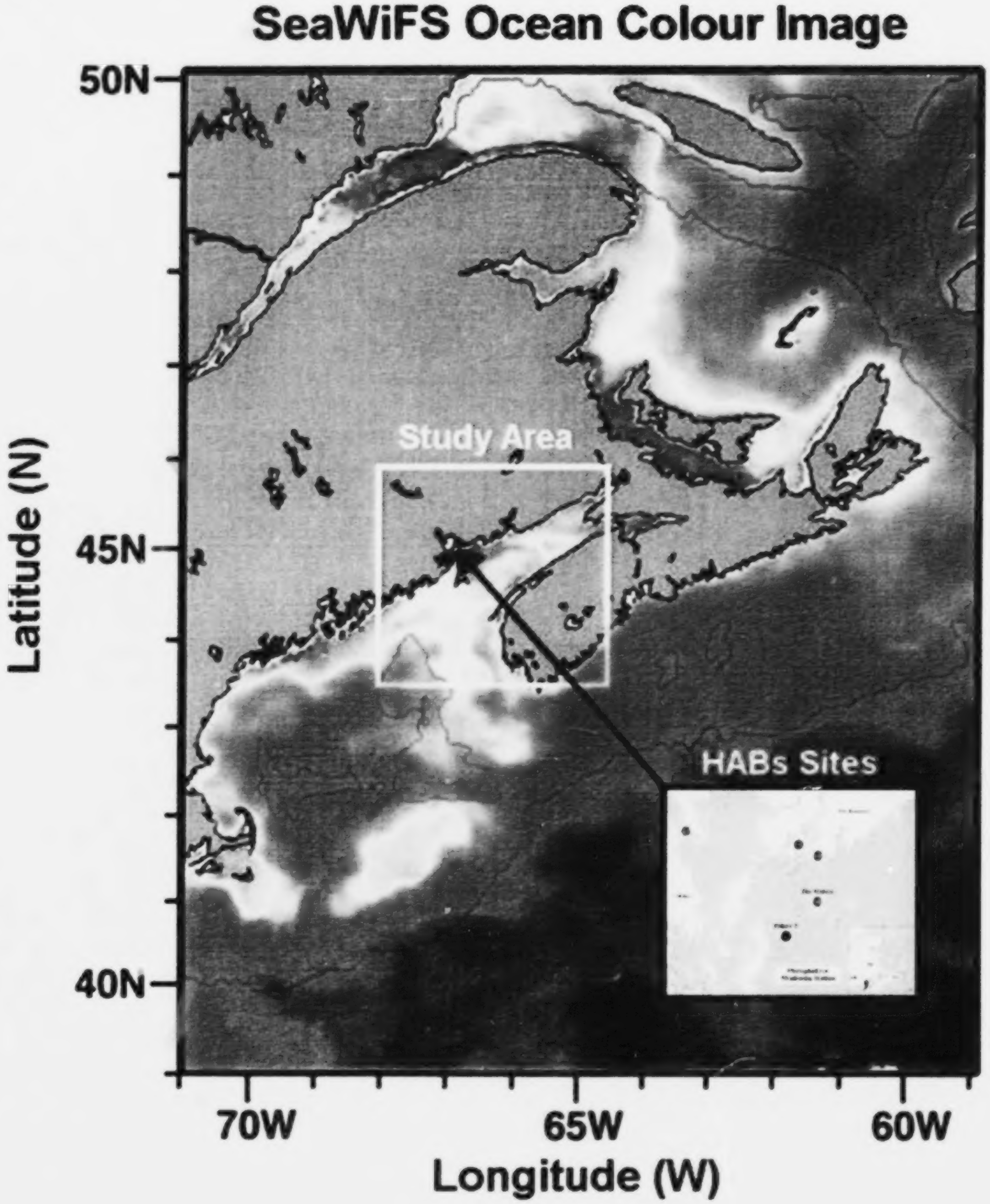
SeaWiFS Ocean Colour Image
50N
45N
40N
Latitude (N)
Study Area
HABs Sites
70W
65W
60W
Longitude (W)

Fig. 1. Example SeaWiFS ocean color image, showing the Bay of Fundy study area and harmful algal bloom (HAB) monitoring stations (inset).

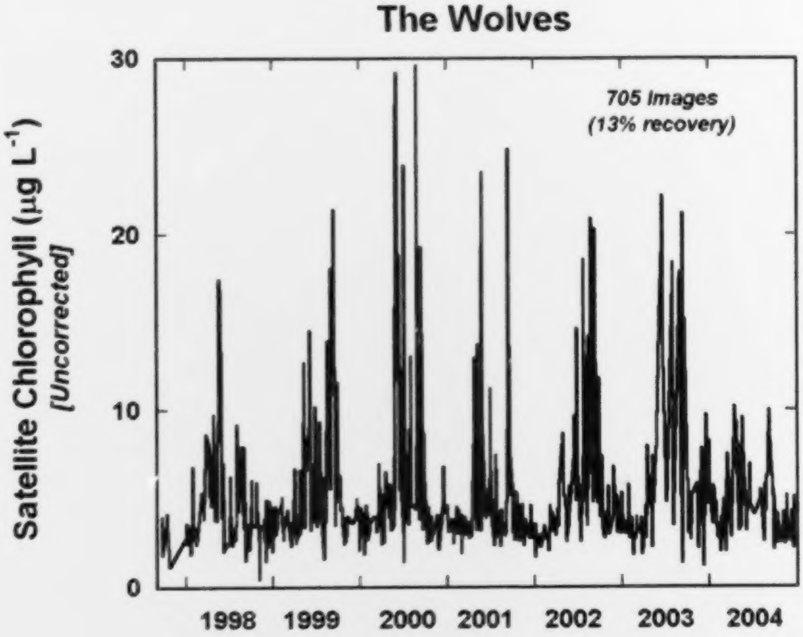

Fig. 2. Uncorrected time series of satellite chlorophyll data collected at the Wolves Islands area, 1998-2004.

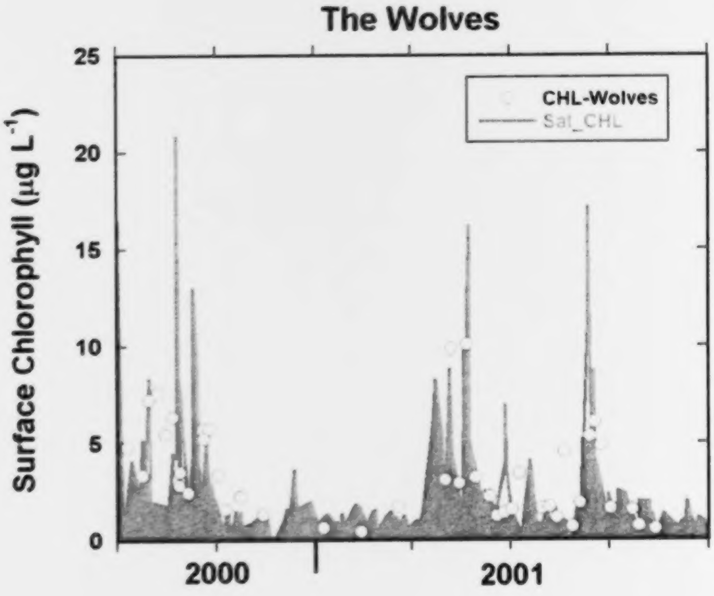

Fig. 3. Uncorrected satellite chlorophyll levels and measured surface chlorophyll data from the Wolves Islands area in 2000 and 2001.

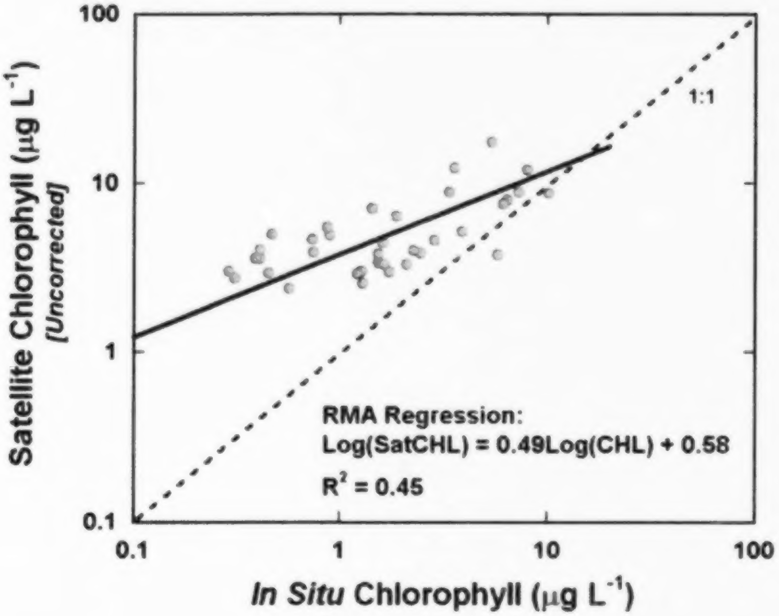

Fig. 4. Regression of uncorrected satellite chlorophyll estimates and measured surface chlorophyll levels from the Wolves Islands and Prince 5 monitoring stations.

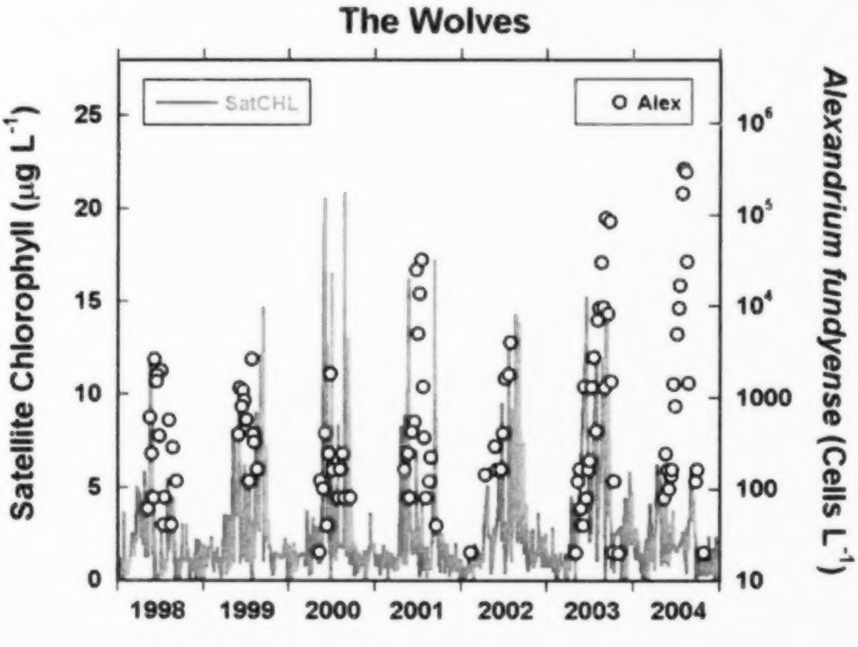

Fig. 5. Corrected satellite chlorophyll levels (SatCHL) and measured abundance of *Alexandrium fundyense* (Alex) at the Wolves Islands, 1998-2004.

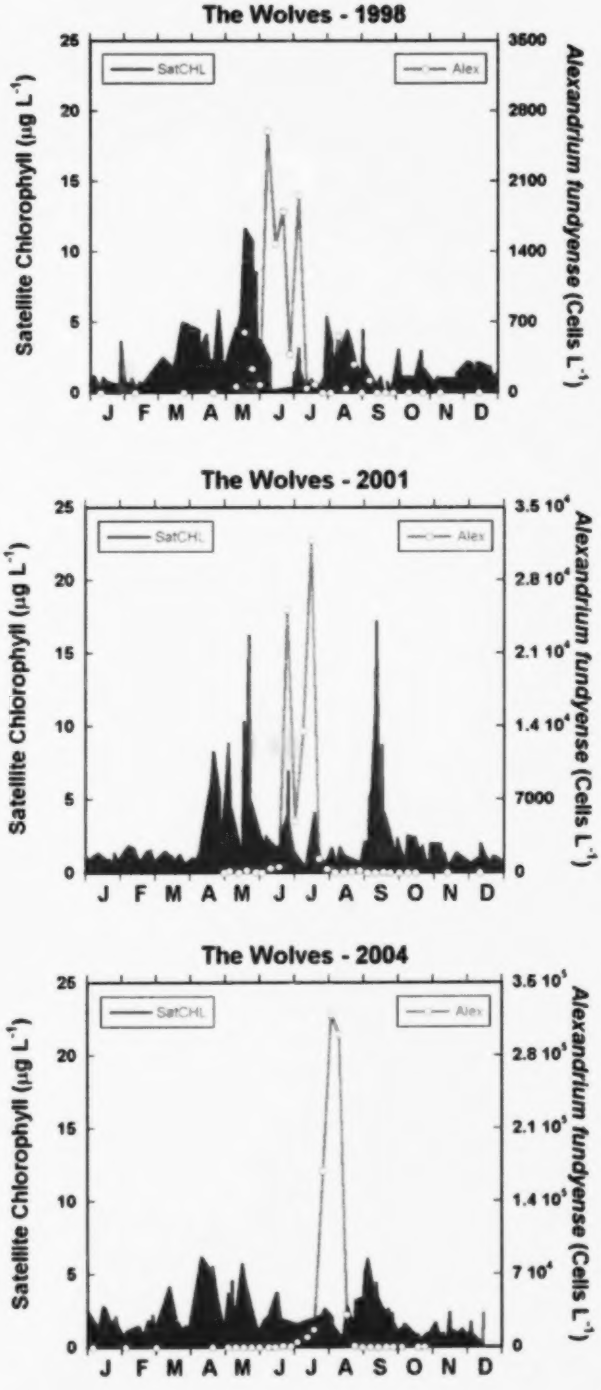

Fig. 6. Corrected satellite chlorophyll levels and measured abundance of *Alexandrium fundyense* at the Wolves Islands, 1998, 2001, and 2004.

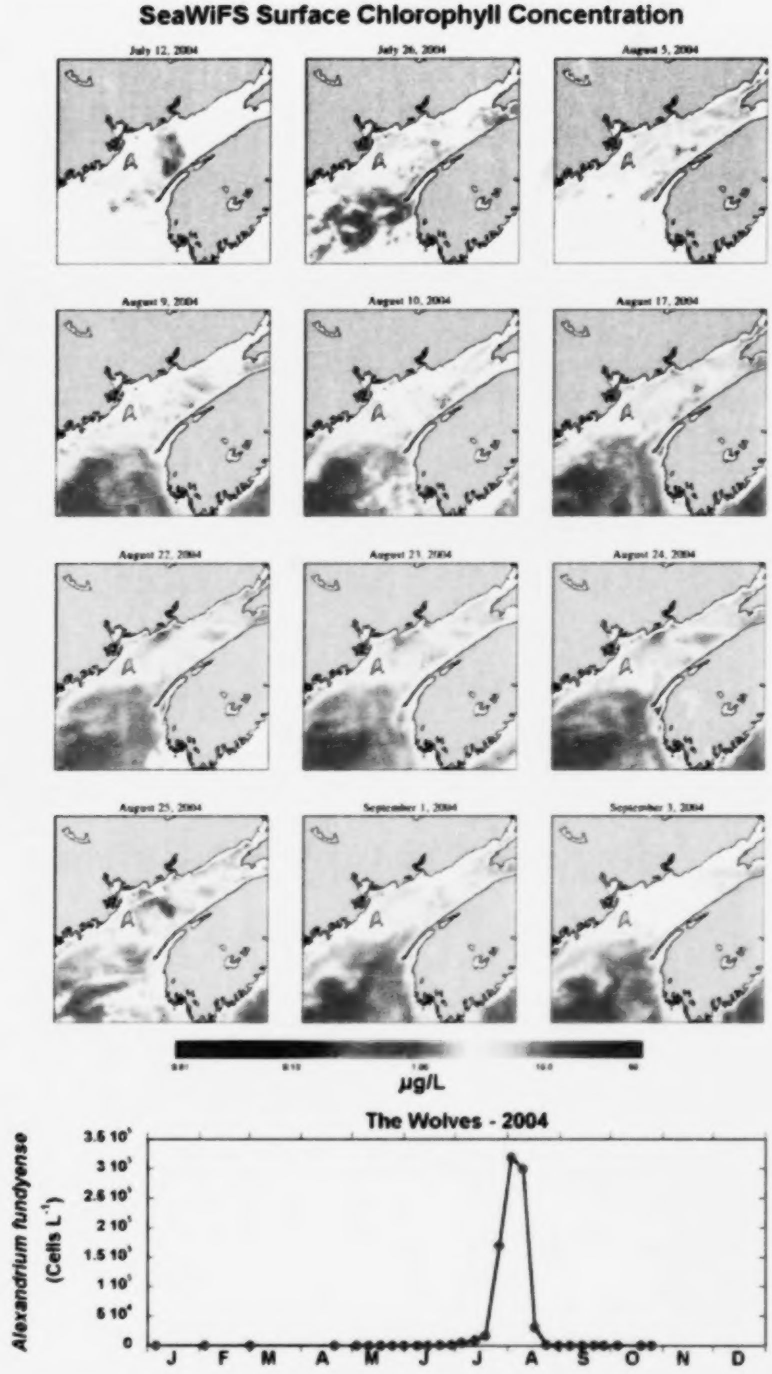
SeaWiFS Surface Chlorophyll Concentration
July 12, 2004
July 26, 2004
August 5, 2004
August 9, 2004
August 10, 2004
August 17, 2004
August 22, 2004
August 23, 2004
August 24, 2004
August 25, 2004
September 1, 2004
September 3, 2004
µg/L
The Wolves - 2004
Alexandrium fundyense (Cells L-1)
3.5 10^5
3 10^5
2.5 10^5
2 10^5
1.5 10^5
1 10^5
5 10^4
0
J F M A M J J A S O N D

Fig. 7. Images showing spatial data provided in SeaWiFS images for July-August 2004. The graph of the abundance of *Alexandrium fundyense* at the Wolves Islands during 2004 shows the large bloom that occurred in July-August.